

Author's Response

In this document we list the points raised by both referees and our responses verbatim (in grey and blue font, respectively) and describe in detail how and where we implemented this in the revised manuscript using red font. Any line numbers in red refer to the [track-changes file](#), while all other line numbers are taken verbatim from the referee's comments and our responses and refer to the initial submission.

Response to Anonymous Referee #1

General comments

The presented manuscript introduces a new approach determining the influence of granular flows on mast-like structures. It addresses an important question in the structural designing process: How high does an avalanche run up and what pressure acts on a structure? The concept of separating run up height from the height of relevant pressure is described and well justified. Although simplifications were necessary, these are stated on the one hand and, on the other hand, the results demonstrate an improvement over existing approaches. Relating to this only Swiss guidelines are referenced, while a similar approach is also defined in a recently published Austrian standard (ÖNORM B 4801). Including this standard could further emphasize the importance of the topic.

- We thank the referee for pointing this out.

The assumption that run-up height defines the vertical extent of the design pressure is indeed not a Swiss particularity but occurs in guidelines across the Alpine countries. We include ÖNORM B 4801 alongside the other references where this is introduced to further emphasize the broad relevance.

Wherever we referred to the *Swiss guidelines*, we now generally say *guidelines* where applicable and define which guidelines we refer to in lines 27-29, and 44-46. In lines 60-64 and 288-290, we additionally discuss the ÖNORM B 4801 approach.

Specific comments

1. Title: The authors could reconsider the title of the publication to clearly indicate that their results are based on numerical simulations.

- We agree that the numerical basis of the work should be unmistakable.

We change the title to: "Distinguishing run-up height from pressure distribution during avalanche impact on narrow obstacles: mechanisms and semi-empirical prediction from three-dimensional simulations".

We changed to title to: *Distinguishing run-up height from pressure distribution during avalanche impact on narrow obstacles: mechanisms and semi-empirical prediction from three-dimensional simulations*

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2. Line 16: In this sentence the authors define snow avalanches as natural granular flows. In my opinion granular flows are conceptual models that provide an approximation to nature.

- We agree; the granular-flow description is a modeling idealization rather than a true analogy.

In the revised manuscript, the opening sentence refers to gravitational mass movements, and the granular-flow concept is explicitly mentioned as an idealized analogy at its first use.

In line 18, we write *gravitational mass movements* and introduce granular flows as a modeling idealization in line 54-55.

3. Line 110; 391: How was the value of 25kPa chosen?

- The reference pressure is a normalization constant, and its choice affects only how compressibility is labeled, not the results. For a given hardening parameter, Eq. (A2) maps monotonically onto a density-increase factor, so a different reference pressure would re-scale the numerical values of the parameter but leave the one-to-one correspondence with the hardening parameter, and therefore every result and fit, unchanged. Within that freedom, 25 kPa was selected for three reasons: (i) consistency with our previous study (Kohler et al., 2026), which uses the same reference; (ii) it lies above the initial pre-consolidation pressure of 10 kPa, so the parameter characterizes plastic compaction rather than the elastic response; and (iii) it is low enough that the softest hardening parameter considered does not yield an unrealistically large density increase. We add this justification to Appendix A1, which we move to supplementary material in the revised manuscript.

In line 125, we emphasize that the reference pressure is selected arbitrarily. More justification is given in Supplementary Material S1 line 11-15 where we included the argumentation from above. Note that what was previously the appendix is now relocated to Supplementary Material S1 and S8.

4. Line 118: What is meant by "...sufficiently large to minimize boundary effects and adjusted based on the compressibility"? It would be helpful to clarify the underlying assumptions.

- The numerical setup is identical to our previous study (Kohler et al., 2026), where the sensitivity of the results to the domain width was tested directly. Side wall effects were assessed through a sensitivity analysis on the total force. Compressibility had a principal effect on the setup width required to minimize side wall effects. Thus, the required setup width grows with the hardening parameter, which is why the width is prescribed through the relation given in the caption of Fig. 2. In the revised manuscript, we state this rationale briefly.

In line 135-137 we clarified that this is taken from our previous publication in which we assessed this through a sensitivity analysis. Similarly, we improved clarity in the caption of Figure 2, which gives the corresponding width parametrization depending on the hardening parameter.

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5. Figure 3(a): It would be helpful to explain the pronounced drop of the upper envelope of $FR=5$ at $t/t_{max} = 0.55$.

- In the revised manuscript, we add a brief explanation to the caption.

The drop is an artifact of the run-up sampling rather than a physical event. Run-up height is defined as the maximum vertical position of the material points within the centered 1.5 m-wide strip upstream of the obstacle (Fig. 2). At high velocity, material is ejected upward and follows a largely ballistic trajectory; when the highest such particle leaves the sampling strip, the maximum falls discontinuously to the next-highest particle inside the strip. In this context, we note that this is precisely the reason why our analysis is based on steady-state means rather than on instantaneous extremes.

We included an explanation directly in the caption of Figure 3.

Technical comments

1. Some full stops are missing at the end of figure captions.

- We correct this in the revised manuscript throughout.

We added the missing full stops to all figure and table captions.

2. Parts of the text in figure A1 is hard to read ("2.5 dx"). Adding a halo or outline around the text could improve readability.

- In the revised manuscript, we add a halo to the annotation.

We added a dark background to the figure, which is now in Supplementary Material S1.

3. Figure 8: Since λ is mentioned before ζ in the text (Line 293), the panels a and b could be swapped for consistency.

- We agree that the inconsistency should be resolved.

The panel order follows the order in which the two coefficients are introduced in the derivation, with the quasi-static magnification factor defined in Eq. (8) and the dissipation factor in Eq. (10). Swapping the panels would put the figure at odds with the equations. In the revised manuscript, we therefore reverse the order of the two coefficients in the sentence so that text, equations, and figure are consistent.

In line 325-326, we swapped the occurrence of the coefficients in the sentence.

4. Line 340-341: Please check sentence structure

- We agree that the sentence is long and cluttered. In the revised manuscript, we rewrite the sentence and split it into two.

We rephrased the sentence in line 377-379.

5. Figure A2/A4: The variable ϕ is presented in different styles to Figure 1. A uniform notation is recommended.

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- In the revised manuscript, we regenerate the appendix figures using the notation of the main text.

We regenerated the figures with the notation of the main article. These figures are now part of Supplementary Material S8.

References

Austrian Standards International: ÖNORM B 4801: Technischer Lawinenschutz – Einwirkungen, Bemessung und Instandhaltung, Austrian Standards International, Vienna, 134 pp., 2024.

Kohler, M. J., Gaume, J., Ancey, C., and Sovilla, B.: 3D Numerical Modeling of Compressible and Cohesive Granular Flow Impact on Narrow Obstacles, Computational Particle Mechanics, 13, 79–96, <https://doi.org/10.1016/j.cpm.2025.11.005>, 2026.

Response to Anonymous Referee #2

General

As a practicing engineer, I appreciate the author's efforts to improve on methods to calculate pressure height distribution on narrow objects. I like the definition of pressure height. The rheology-flow regime parameters seem reasonable.

Since the design of tall narrow structures subject to avalanche impact is often determined by the overturning moment rather than the total force, the heights of impact are critical for design. The simplified point-mass methods overestimate impact pressure heights and can lead to overly-conservative designed, unless modified by engineering judgment.

- We thank the reviewer for pointing this out.

To further strengthen the motivation of the paper, we add a sentence on the susceptibility of bending moments of such structures to the introduction of the revised manuscript.

In lines 28-29, we now state that the vertical extent of the load sets the lever arm of the resultant force and hence the base moment, which typically governs the design of narrow structures.

Specific

1. The graphical abstract (adapted from Margreth, et.al., 2015) shows a curious pressure distribution with the highest pressure at the base. This differs from Fig. 1 in the reference.
 - This is intentional, and we recognize that this is unclear from the current caption, which only hints at this by saying "adapted from" rather than "adopted from". The indicated load shape shown is inspired by our own results: both the gravity-driven and the inertia-driven cases in Fig. 5 exhibit impact pressure increasing toward the obstacle base, which we attribute to flow deflection at the dead zone (line 200 to 205), consistent with the

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flume observations of Armanini et al. (2011). The distribution is deliberately drawn with dashed lines to indicate a schematic rather than a proposed idealized load model, since this paper concerns the vertical extent of significant pressure and not the shape of the design distribution. In the revised manuscript, we make this explicit in the figure caption.

We added a caption to the graphical abstract indicating that the pressure distribution is an arbitrary schematic and not a proposed shape.

2. Constitutive model oversimplifies, but is reasonable.

- We agree that the constitutive model has its limitations and more complex formulations exist, like thermo-mechanical or two-phase types (see point 6). It is, however, still one of the most advanced models applied to study snow avalanche impact, especially considering the 3D nature of the simulations.

3. Results for the inertia-driven regime ($Fr=5$) represent common conditions for design. However, Froude numbers up to 10 occur for dry dense flowing avalanches. Why were higher Froude numbers not modeled?

- We agree that this needed to be stated more explicitly, and we clarify it in the revised manuscript.

Since the applied numerical method does not capture particle suspension, we constrained the analysis to velocities typical of dense flow avalanches.

In our study, we present data up to $Fr = 7$, which corresponds to a velocity of 29 m/s, given the flow height of $H = 1.75$ m. Rudolf-Miklau et al. (2014) give 20 to 40 m/s as the typical velocity range of dry flowing avalanches and 30 m/s as the lower bound of the typical range of powder snow avalanches. This threshold is of the same order of magnitude as the observations by Gubler et al. (1986).

Our upper simulated velocity of 29 m/s therefore sits at the margin at which powder snow avalanches begin to be encountered, while remaining within the velocity range of dry flowing avalanches. Extending the range further would move the simulations outside the regime the numerical model can represent.

Beyond this, we do not expect additional simulations at higher Fr to change our conclusions. Pressure height saturates at a fitted Froude number of $Fr_{sat} = 1.5$ (Table 3), far below the maximum simulated value, and is essentially constant from $Fr = 2$ to $Fr = 7$ (Figs. 4b and 6). Run-up height continues to scale with the velocity squared across the entire simulated range, with no sign of a change in scaling up to $Fr = 7$, which supports extrapolation of Eq. (10) beyond the simulated range for the run-up branch.

We improved the motivation of the selected velocity ranges in lines 146-150. There, we mention the limitations of the model regarding particle suspension and the typical velocity ranges reported for powder snow avalanches.

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We want to add to our previous response, that the occurrence of powder snow avalanches is a question of velocity rather than Froude number.

4. Fig. 3 illustrates findings nicely and is consistent with full scale avalanches.
 - We thank the referee for this confirmation against field experience.
5. An example calculation and comparison with traditional method for the proposed empirical method might be helpful. One possibility is Example E.2 , Load on a 20m mast in the 2009 EC Design of Avalanche Protection Dams.
 - We thank the referee for this concrete and useful suggestion. We add two example calculations as an appendix to the revised manuscript. One is in close agreement with the scenario in the EC handbook, and the other is a slower impact scenario.

For this, we relabel the current appendix as supplementary material to keep the main paper body concise.

We added the suggested calculation example as an appendix to the manuscript. We even extend the example by considering a slower impact scenario, highlighting that our approach is less conservative for fast impacts, and more conservative for slow impacts. In the Supplementary Material S9, we give continuous curves of base shear and base moment over a velocity range for a fast and a slow flow regime.

6. There is no discussion of temperature or wet avalanches flows. This might be stated directly or describe limits of temperature and/or water content that the methods are limited to. Conversely, state the “ideal” conditions where confidence is highest.
 - The applied constitutive model is purely mechanical and single-phase, with neither thermo-mechanical coupling nor a liquid-water phase. It therefore cannot represent the evolution of mechanical properties with temperature or water content. It describes a snow avalanche as a compressible cohesive-frictional granular material with a fixed set of bulk mechanical properties.

For the instant of impact, we consider it a good approximation for the present application to treat the bulk rheological behavior as constant. The parameter sweep over friction (M), cohesion (β), and plastic compressibility ($\chi_{pc}=25$) was designed to span the bandwidth of snow avalanche rheology. Wet snow is mechanically characterized by higher cohesion and altered friction, at least up to a certain liquid water content, and we are confident that the corresponding behavior lies inside the swept ranges. We therefore expect to capture the mechanical response at impact, while the thermal and hydraulic pathways that produce those properties are not modeled, and their evolution during an event lies outside the scope of the study.

We would like to stress that the purpose of the sweep is not to enlarge the parameter space of the proposed design equations, but to reduce it. Friction and cohesion are combined into a single effective internal friction M' (Eq. 2), plastic compressibility is shown to be of secondary importance and is omitted from the pile-up term (Eq. 8), and

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the bulk density is held fixed at the value common in avalanche engineering. The resulting formulations for run-up and pressure height therefore contain one rheological input, M' , for which we give recommended ranges obtained by mapping the guideline dissipation factors onto our results: $M' \approx 0.45$ to 0.65 for dry, loose snow avalanches and $M' \approx 1.0$ to 1.5 for dense snow avalanches (Sect. 4.2, Fig. 8 and 9). A practitioner thus selects a value from an avalanche-type table, as in current practice, and no temperature or liquid-water variable enters the design method.

A more explicit treatment is currently limited by the state of the art in snow mechanics rather than by the numerical framework. The literature on wet snow mechanics is sparse, and the available parametrizations of mechanical properties remain uncertain, since there is no established method to reliably control, or even measure, the liquid water content of snow in mechanical experiments. Should such parametrizations become available, the bulk mechanical behavior of our model could in principle be parameterized with them directly.

Following the referee's suggestion, we state the conditions of highest confidence explicitly in Sect. 5 of the revised manuscript: dense, (cohesive-) frictional flow at approximately steady conditions, plug-like or Bagnold velocity profile, velocities up to about 30 m/s, relative obstacle widths in the range $w/H = 0.5$ to 3 , and at approximately constant temperature and liquid water content at the instant of impact.

We added a corresponding note in the methods section, line 98-100. We raise this limitation again in the Conclusions, line 407-410, as well as in the bullet points stating the “ideal conditions” of application, line 420.

7. On line 242, “the spirit of the Swiss guidelines” is referenced. What is meant by this?

- We acknowledge that the phrase is vague and we replace it with an explicit statement of what is retained and what is changed compared to the Swiss guidelines.

We retain: (i) the velocity head from Bernoulli's principle as the basis for the inertia-driven contribution; (ii) an energy dissipation factor λ in the denominator; (iii) a width-correction factor $f(w/H)$; (iv) the terminology of Margreth et al. (2015), so that the proposed relations remain immediately readable to users of the guidelines.

We change: (i) the structure to an additive decomposition, in which a quasi-static term is added to the dynamic contribution; and (ii) the selection of λ . In place of the dichotomy between dry, loose and dense snow avalanches, we introduce a continuous parametrization through the effective internal friction M' , and we provide the M' ranges that reproduce the two canonical avalanche types (Sect. 4.2), so that established engineering judgment remains transferable.

We changed this phrase in line 267-271 and now clearly state which elements of the guideline formulation we retain and where we depart from it.

8. My experience and judgment are consistent with the finding that pressure height becomes “saturated” and empirical methods are off at high Fr. Numbers. Fig. 5 illustrates this nicely.

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- We thank the referee for this confirmation against field experience.
- 9. Perhaps the most interesting finding of the numerical approach is the w/H affect for narrow structures. Lines 332-333 are relevant for design purposes. I calculate a 23% underestimation of $f_r(w/H)$ for dense flow at $w/H=0.5$ based on Fig. 10. This is very interesting and important for design purposes. I look forward to seeing this finding tested, verified or modified as new data becomes available.
- We thank the reviewer for acknowledging this result. This is the basis for our recommendation to limit $f(w/H)$ to a minimum of about 0.7 for $w/H < 1$, which covers the discrepancy with a small margin.

Further research on this, both experimental and numerical, is ongoing.

References

Armanini, A., Larcher, M., and Odorizzi, M.: Dynamic Impact of a Debris Flow Front against a Vertical Wall, Italian Journal of Engineering Geology and Environment, 1041–1049, <https://doi.org/10.4408/IJEGE.2011-03.B-113>, 2011.

Margreth, S., Stoffel, L., and Schaer, M.: Berücksichtigung der Lawinen- und Schneedruckgefährdung bei Seilbahnen. Ein Leitfaden für die Praxis, WSL Berichte 28, WSL-Institut für Schnee- und Lawinenforschung SLF, Davos; Eidg. Forschungsanstalt für Wald, Schnee und Landschaft WSL, Birmensdorf, 43 pp., 2015.

Rudolf-Miklau, F., Sauer Moser, S., and Mears, A. I., eds.: The Technical Avalanche Protection Handbook, Wiley, 1 edn., <https://doi.org/10.1002/9783433603840>, 2014.

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