Response to Anonymous Referee #2

We would like to thank the reviewer for taking the time to review our manuscript and for the constructive feedback, which will help improve its quality. Below, we list each comment verbatim, give our response, and describe how we address it in the revised manuscript.

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.

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 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.
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.

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.

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 (beta), 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 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′ ≈ 0.45 to 0.65 for dry, loose snow avalanches and M′ ≈ 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.

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 lambda 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 lambda. 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.

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.

    - 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., Sauermoser, S., and Mears, A. I., eds.: The Technical Avalanche Protection Handbook, Wiley, 1 edn., https://doi.org/10.1002/9783433603840, 2014.

Gubler, H., Hiller, M., Klausegger, G., and Suter, U., Messungen an Fliesslawinen, SLF, 1986