

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

Michael J. Kohler^{1,2}, Johan Gaume^{1,3}, Christophe Ancey², and Betty Sovilla¹

¹WSL Institute for Snow and Avalanche Research SLF, Flüelastrasse 11, 7260 Davos Dorf, Switzerland

²EPFL Environmental Hydraulics Laboratory, Station 18, 1015 Lausanne, Switzerland

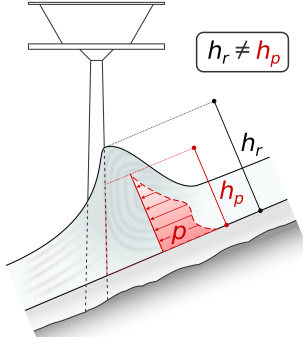
³ETH Zurich Chair of Alpine Mass Movements, Stefano-Francini-Platz 5, 8093 Zurich, Switzerland

Correspondence: Michael J. Kohler (michael.kohler@slf.ch)

Abstract. In many avalanche engineering guidelines, run-up height is assumed to define the vertical extent of significant impact pressure of snow avalanches on narrow obstacles, such as cableway masts or transmission towers. Laboratory experiments indicate that this assumption is invalid in fast, inertia-driven regimes; however, the underlying mechanisms remain poorly understood, limiting the physical basis for improving design practice. To clarify these mechanisms and refine engineering formulations, we conduct a comprehensive numerical investigation using a three-dimensional Material Point Method, varying avalanche velocity and rheological parameters. Our results substantiate that run-up height and the vertical extent of significant impact pressure, which we term *pressure height*, are distinct quantities governed by different mechanisms. Both include a gravity-driven component controlled by avalanche rheology and independent of flow velocity. In fast flows, however, the two quantities diverge: run-up height gains a dominant inertia-driven component that scales with the square of the flow velocity, while avalanche rheology controls energy dissipation. Pressure height, by contrast, remains velocity-independent. This divergence arises from flow deflection at a dead zone near the obstacle base, where momentum is redirected and impact pressure concentrates. Building on these distinctions, we propose separate semi-empirical formulations for run-up height and pressure height. The run-up formulation follows the structure of the most common avalanche engineering guidelines, but replaces simplified avalanche-type classifications with a rheological parametrization. The pressure height relation adopts the same framework, while reflecting its distinct, velocity-independent governing mechanism.

1 Introduction

Gravitational mass movements such as snow avalanches are major natural hazards in mountainous regions, causing loss of life and substantial damage to infrastructure (Techel et al., 2016; Ortner et al., 2023). Assessing their destructive power is a central component of hazard mitigation and requires understanding the physical processes that govern impact. A key process is run-up: the upward rise of material along the upstream face of an obstacle as the flow decelerates and transfers momentum to the structure (Iverson et al., 2016). Run-up height is a central engineering quantity across a broad range of structures. For wide obstacles such as avalanche dams, it determines crest elevation and retention capacity (Jóhannesson et al., 2009). For



Graphical abstract / key figure (not intended to be part of the paper): Schematic representation of an avalanche impacting a narrow obstacle, illustrating that the run-up height does not determine the pressure distribution height. The shape of the pressure distribution is intentionally shown as a dashed line to emphasize that this is an arbitrary schematic representation and not a proposed shape (adapted from Margreth et al., 2015).

narrow obstacles such as cableway masts or transmission towers, which are often located in remote and exposed terrain (Vallero et al., 2026), run-up height sets the risk of damage to protruding elements that may be struck by upward-moving material. More
 25 consequentially, it is also assumed to define the vertical extent of idealized impact pressure distributions in guidelines across the Alpine countries (Margreth et al. (2015), ÖNORM B 4801 (2024)). The vertical extent of this load sets the lever arm of the resultant force and therefore the base moment, which typically governs the design of such narrow structures. The wide–narrow distinction, classically defined by an obstacle width of approximately three times the flow height, or 2m, according to Margreth et al. (2015), has important implications for the mechanical description of the problem. For wide obstacles, the impact problem
 30 can be approximated under plane-strain conditions, enabling a quasi-two-dimensional analytical description (e.g., McClung and Mears, 1995; Hákonardóttir, 2003; Mejean et al., 2017; Faug, 2021). For narrow obstacles, however, the flow partially bypasses the structure laterally, making the impact problem inherently three-dimensional (Wu et al., 2023; Lin et al., 2025). This complicates the mechanical description and requires many restrictive assumptions in any analytical treatment (cf. Faug et al., 2010; Bartelt et al., 2018).

35 In the absence of generally accepted analytical solutions for narrow obstacles, engineering practice often relies on empirical formulations calibrated against observations to predict run-up height (Salm et al., 1990). The most prominent approach is based on the velocity head from Bernoulli’s principle

$$h_v = \frac{v^2}{2g}, \quad (1)$$

which describes the transformation of kinetic energy to potential energy upon impact. Therein, h_v denotes the velocity head
 40 expressed as an equivalent height, v is the flow velocity, and g is the gravitational acceleration. This concept was already used by Voellmy (1955) in his pioneering work on snow avalanche dynamics and has since been adopted in snow avalanche engineering guidelines across the Alpine countries (Margreth et al. (2015), ÖNORM B 4801 (2024), given their widespread application, henceforth referred to as *the guidelines*). In the guidelines, Eq. (1) is augmented by two empirical factors to account for the

influence of obstacle width and energy dissipation (cf. Sect. 4 for the full equation). Avalanche rheology is only crudely reflected
45 in the energy dissipation factor, without an explicit link to measurable material constants. Yet experimental observations show
that flow rheology strongly influences the morphology of flow–obstacle interaction (Choi et al., 2015; Armanini et al., 2011),
implying that the physical mechanisms governing run-up are poorly represented by this framework and that predictive reliability
is limited.

The limitations extend beyond run-up height estimation itself. In laboratory experiments on supercritical granular flows
50 impacting narrow obstacles, Hauksson et al. (2007) showed that the total impact force became independent of obstacle height
once it exceeded approximately three flow heights, which is substantially below the corresponding run-up heights. As granular
flows are a common modeling idealization for snow avalanches (e.g., Savage and Hutter, 1989; Bartelt et al., 1999), this
result suggests that run-up height does not reliably indicate the vertical extent of impact pressure in such avalanche impact
configurations, contrary to the assumption in the guidelines. Sovilla et al. (2008b) further demonstrated that the guidelines
55 formulation can produce physically inconsistent force predictions, providing additional evidence that the framework lacks a
sound physical basis. For fast, fluidized avalanches ($v > 28 \text{ m s}^{-1}$), Margreth et al. (2015) partly acknowledge excessive run-up
height estimates: following Jóhannesson et al. (2009), they suggest limiting the run-up height to $v/(10 \text{ s}^{-1})$. ÖNORM B 4801
(2024) suggests a different adaptation, derived from three-dimensional simulations of a water-like liquid impacting mast-like
obstacles (Huber et al., 2021). The two limits deviate markedly from each other. Neither is well founded: no derivation is
60 published for the former, and the latter rests on a fluid idealization that omits avalanche rheology, which strongly influences
flow–obstacle interaction (Choi et al., 2015).

Addressing these inconsistencies requires capturing the transient three-dimensional impact process while explicitly accounting
for avalanche rheology. Recent numerical studies of snow avalanche impact on narrow obstacles could not resolve run-up
formation due to computational constraints imposed by their discrete modeling approach (Kyburz et al., 2020, 2022). Continuum
65 approaches based on the Material Point Method (MPM) are a computationally efficient alternative, capturing both transient
run-up dynamics and avalanche rheology, as recently demonstrated for impact pressure analysis (Kohler et al., 2026a). However,
run-up formation and its relation to impact pressure distribution remain uninvestigated.

Here, we pursue two main objectives. Our first objective, addressed in Sect. 3, is to clarify the physics of run-up on vertical
narrow obstacles. Specifically, we investigate how run-up height depends on bulk rheological parameters and how it relates
70 to the vertical extent of significant impact pressure. Our second objective, addressed in Sect. 4, is to translate these insights
into a practical framework. We propose a semi-empirical extension of the velocity head formulation that explicitly incorporates
rheological parameters and introduce a new metric to better quantify the vertical extent of significant impact pressure.

Together, these objectives address a gap that has direct consequences for efficient structural design: the assumption that run-up
height defines the vertical extent of significant impact pressure on narrow obstacles is not physically justified, and this paper
75 provides both the mechanistic explanation and a practical alternative.

2 Methodology

2.1 Numerical framework

2.1.1 The material point method (MPM)

MPM combines the advantages of particle-based and grid-based methods, making it ideal for large-deformation modeling of granular flows (Kamrin et al., 2024). In MPM, a body is discretized into Lagrangian material points (MPs) carrying all state variables, such as deformation or stress states. The MPs move through an Eulerian background grid used to compute spatial derivatives and solve the momentum balance and constitutive equations (Sulsky et al., 1994; Stomakhin et al., 2013). In each time step, quantities are transferred between MPs and grid nodes using mapping functions, and the grid is reset. This prevents mesh distortion issues, typical of methods employing Lagrangian meshes.

We employ the three-dimensional (3D) single-phase MPM framework of Gaume et al. (2018) using quadratic B-Spline mapping functions, which closely follows the explicit symplectic Euler scheme of Stomakhin et al. (2013). Further details can be found in the original publications, the references therein, and our previous work (Kohler et al., 2026a). This framework, together with its constitutive model for snow, has been validated and used extensively in numerical avalanche dynamics (e.g., Li et al., 2021; Védérine et al., 2022).

2.1.2 Constitutive model

The avalanching material is modeled using the large-strain elasto-plastic law for snow of Gaume et al. (2018), built around a cohesive Modified Cam–Clay (cMCC) plasticity model (Roscoe and Burland, 1968). The macroscopic rheology is mainly controlled by three plasticity parameters: the internal friction M , a cohesion parameter β , and the plastic compressibility $\chi(p_c)$ (Li et al., 2024). The model does not feature a liquid water phase, nor does it account for thermo-mechanical coupling. Effects of temperature and liquid water content are therefore assumed to be encoded in these three parameters and treated as constant at the instant of impact.

M and β can be combined into an effective internal friction (Ritter et al., 2020)

$$M' = \frac{\beta + 1}{(1 - \beta)\sqrt{2\beta + 1}} M, \quad (2)$$

which can be interpreted as a proxy for the material’s angle of repose (Metcalf, 1966; Willibald et al., 2020; Eidevåg et al., 2022). M' is related to the Coulomb friction angle φ' through $\varphi' = \arcsin(3M'/(M' + 6))$ (Ortiz and Pandolfi, 2004) (cf. Fig. 1). We use M' as a primary rheological descriptor throughout this study, as it captures the combined effect of friction and cohesion in a single physically interpretable parameter.

Both M and β appear in the cMCC yield function

$$y(p, q) = q^2(1 + 2\beta) + M^2(p + \beta p_c)(p - p_c), \quad (3)$$

expressed in terms of the mean (compressive) stress $p = -\text{tr}(\boldsymbol{\tau})/3$, and the *von Mises* equivalent stress $q = (3/2 \boldsymbol{s} : \boldsymbol{s})^{1/2}$, where $\boldsymbol{s} = \boldsymbol{\tau} + p\boldsymbol{I}$ is the deviatoric part of the Kirchhoff stress tensor $\boldsymbol{\tau}$. The elastic behavior is described through a Saint-Venant–

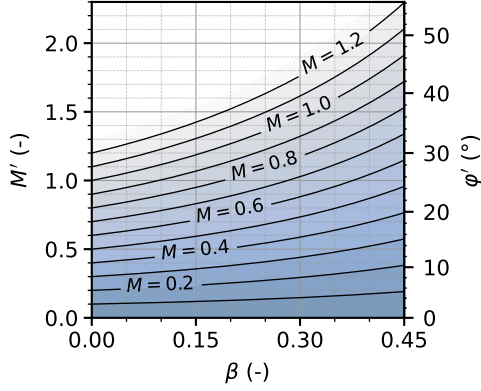


Figure 1. Effective internal friction M' and effective internal friction angle φ' over β for different values of M , calculated from Eq. (2).

Kirchhoff law. The yield function forms a semi-elliptical curve in $p - q$ space (cf. Kohler et al., 2026a), which is a common assumption for highly porous media such as snow, supported by microstructure-based studies (Ritter et al., 2020; Blatny et al., 2021). The pre-consolidation pressure p_c sets the size of the elastic domain: the vertices of the semi-ellipse along the p -axis lie at p_c in compression and at $p_t = -\beta p_c$ in hydrostatic tension, while M controls the vertex in the deviatoric direction and hence the shear strength. For plastic stress states, the plastic strain follows the associative flow rule proposed by Simo and Meschke (1993).

When the material gets compacted, p_c grows, and the yield surface expands according to the hardening law (Ortiz and Pandolfi, 2004)

$$p_c = K \sinh(\xi \max(-\varepsilon_V^P, 0)), \quad (4)$$

where K is the bulk modulus, ξ is a hardening parameter, and $\varepsilon_V^P = \log J_P$ is the plastic volumetric Hencky strain, with J_P the plastic Jacobian (cf. Kohler et al., 2026a, for further details and definitions). Hardening depends solely on volumetric deformation. Compaction ($\dot{\varepsilon}_V^P < 0$) expands the yield surface, whereas dilation ($\dot{\varepsilon}_V^P > 0$) contracts it and causes softening. The hardening parameter ξ controls the rate of this evolution and therefore principally affects the material's plastic compressibility. To aid physical interpretation, we express compressibility through the parameter $\chi(p_c = 25)$, which can be interpreted as a plastic density-increase factor evaluated at an arbitrarily chosen reference pre-consolidation pressure of $p_c = 25$ kPa for a given ξ ; the correspondence between ξ and $\chi(p_c = 25)$ is given in Table 1 and its derivation is given in Sect. S1 in the Supplements.

2.2 Numerical setup

We adopt the conveyor-belt setup of Kohler et al. (2026a), in which the avalanche travels horizontally and impacts a rigid, vertical, rectangular obstacle. The avalanche is driven at a prescribed velocity rather than released from a chute, providing precise control of the flow velocity. The resulting motion resembles a plug flow, which can be seen as an idealization of a sheared avalanche in which we ignore the velocity profile and focus on the average velocity.

Table 1. Fixed and varied material parameters of the avalanche.

fixed material parameters:			
initial bulk density	ρ_0	(kg m^{-3})	300
Young's modulus	E	(kPa)	1000
Poisson ratio	ν	(-)	0.1
bulk modulus ^a	K	(kPa)	416.67
initial pre-consolidation pressure	$p_{c,0}$	(kPa)	10
varied material parameters:			
CSL slope (friction)	M	(-)	{0.0, 0.4, 0.8, 1.2}
p_t/p_c (cohesion)	β	(-)	{0.0, 0.15, 0.3, 0.45}
plastic compressibility	$\chi(p_c = 25)$	(%)	{205.3, 127.1, 107.5, 102.4, 100.7, 100.2} ^b

^a Follows from E and ν : $K = E/(3(1 - 2\nu))$.

^b This corresponds to the hardening parameters $\xi = 0.05, 0.15, 0.5, 1.5, 5$, and 15 , respectively. For snow avalanches at the density used here, the relevant parameter range is $\chi(p_c = 25) \in \{107.5, 102.4, 100.7\}\%$ (i.e., $\xi \in \{0.5, 1.5, 5\}$). Accordingly, we restrict our semi-empirical model fitting to this range.

The initial flow height H and the obstacle width w are fixed at $H = w = 1.75$ m. We simulate a confined strip of the avalanche rather than the full width to limit computational cost, with the domain width W chosen sufficiently large to minimize sidewall effects (cf. Fig. 2). In Kohler et al. (2026a) we assessed these effects through a sensitivity analysis on the total force and found the required width to depend principally on the compressibility, that is, on the hardening parameter ξ . We adopt the same parametrization here. The computational grid spacing is $dx = 0.25$ m. Flow velocity is maintained by frictional sidewalls, while the bottom boundary is frictionless.

For impact scenarios, flow regimes can be characterized by the Froude number $\text{Fr} = v/\sqrt{gH}$, where v is the flow velocity, g is gravitational acceleration, and H is the flow height. Fr expresses the ratio of inertial to gravitational forces: subcritical flows ($\text{Fr} < 1$) are gravity-driven, supercritical flows ($\text{Fr} > 1$) are inertia-driven, and the range $0.3 < \text{Fr} < 3$ is sometimes referred to as transitional (Faug, 2015; Kohler et al., 2026a). Real snow avalanches span a wide range, from slow, dense flows below $\text{Fr} = 1$ to fast mixed powder snow avalanches beyond $\text{Fr} = 7$ (Köhler et al., 2018).

The flow velocity ranges in Table 2 are selected to cover typical dense snow avalanche regimes (Köhler et al., 2018; Sovilla et al., 2008a), as the applied numerical method does not represent particle suspension. Rudolf-Miklau et al. (2014) give 30 m s^{-1} as the lower-bound velocity for powder snow avalanches, a threshold of the same order as the observations of Gubler et al. (1986). This sets the upper limit of our considered velocity to $v = 29 \text{ m s}^{-1}$, corresponding to $\text{Fr} = 7$ at $H = 1.75$ m. The simulations therefore span typical dense flow velocities up to the margin at which powder snow avalanches begin to be encountered.

The material parameter ranges in Table 1 are selected based on previous MPM snow-modeling studies (e.g., Li et al., 2020, 2021; Kyburz et al., 2024). The elasticity parameters E and ν , the initial pre-consolidation pressure $p_{c,0}$, and the initial

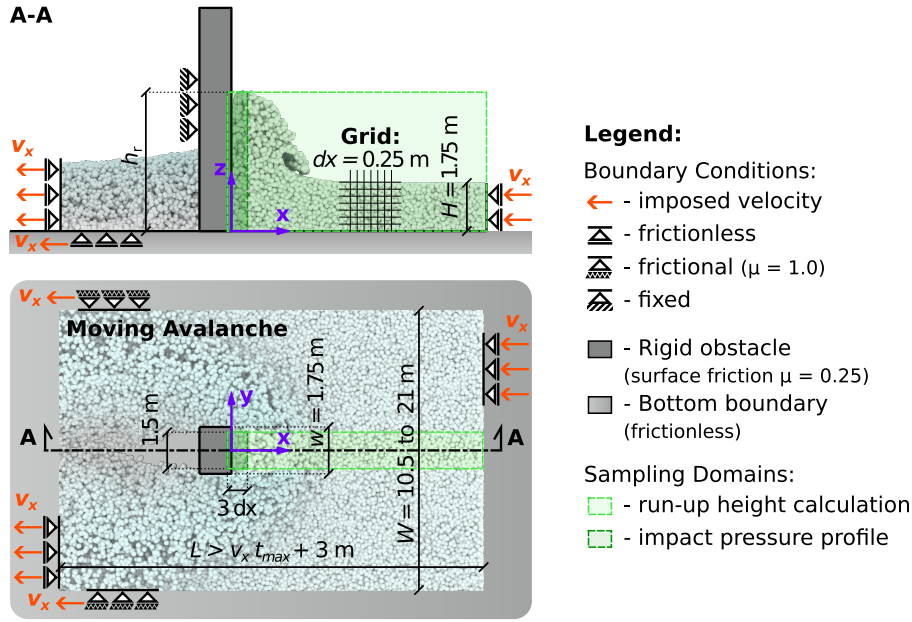


Figure 2. Schematic of the numerical setup, illustrating the dimensions and boundary conditions. The upper panel shows a longitudinal section, while the lower panel provides a top-down view. W follows from $W = (6 + 3 \log(\xi/0.05))w$, with w the obstacle width and ξ the hardening parameter of the avalanching material. This is largely taken from our previous publication (Kohler et al., 2026a).

bulk density ($\rho_0 = 300 \text{ kg m}^{-3}$, a common estimate in avalanche engineering) are kept fixed. For each Fr , we perform at least 48 simulations, combining 4 values of M and β with at least 3 values of $\chi(p_c = 25)$ ($\in \{205.3, 107.5, 100.7\}\%$). Additional compressibility levels, $\chi(p_c = 25) \in \{127.1, 102.4\}\%$, are included for selected M and β combinations. In total, the study comprises 371 simulations.

Table 2. Flow and simulation properties of the numerical setup.

Froude number	flow velocity	simulation duration	avalanche length
Fr	v_x	t_{max}	L
(-)	(ms^{-1})	(s)	(m)
0.1	0.41	60 to 120	27.9 to 52.7
0.3	1.24	55 to 110	71.4 to 139.7
1	4.14	36.7	155.1
2	8.29	5 to 7.5	44.4 to 65.2
3	12.43	5 to 7.5	65.2 to 96.2
5	20.72	5 to 10	106.6 to 210.2
7	29.00	5 to 10	148.0 to 293.0

150 A sensitivity analysis with respect to grid resolution, slope angle, obstacle friction, and obstacle width is provided in Sect. S2 in the Supplements. Results are robust with respect to grid resolution and slope angle. Obstacle friction has a measurable influence, with increasing friction leading to reduced run-up heights. The effect of obstacle width is discussed in Sect. 4.3. Section S3 in the Supplements contains simulation renderings showing characteristic flow morphology for every considered Fr and avalanche rheology.

155 2.3 Postprocessing

In the following, time-averaged values are denoted by an overline (e.g., $\bar{h}_r$), peak values are denoted by a hat (e.g., $\hat{h}_r$), and volume-averaged values by angle brackets (e.g., $\langle \sigma_{xx} \rangle$). We commonly normalize run-up and pressure height by the initial flow height H .

We determine run-up height h_r in each simulation frame as the maximum vertical position of the MPs within a centered
160 1.5 m-wide strip upstream of the obstacle (cf. Fig. 2). Steady-state values are computed as the arithmetic mean over a time span, the temporal position of which is determined by a running deviation analysis. The time span is several seconds long and varies depending on the Froude number. Time history plots and the corresponding averaging time-spans are shown in Sect. S4 in the Supplements.

Impact pressure profiles are obtained by binning the MPs by their z -position at a resolution of $dx/2$ (cf. coordinate system
165 in Fig. 2). For each bin, we compute the volume-averaged streamwise stress σ_{xx} within a domain directly upstream of the obstacle–avalanche interface. The domain extends from $-0.5 dx$ to $2.5 dx$ in the x -direction, over ± 0.75 m in the y -direction, and from 0 to $5H$ in the z -direction, resulting in 70 bins. The x -extent of $3dx$ was chosen to cover the compact support of the quadratic B-spline interpolation functions (cf. Sect. S1 in the Supplements).

3 Dependence of run-up and impact pressure distribution on flow regime and material rheology

170 3.1 Run-up height and its rheological contributors

Avalanche rheology controls run-up height differently depending on the flow regime. Figure 3 (a) shows the time evolution of run-up height for a gravity-driven ($Fr = 0.1$), a transitional ($Fr = 1$), and an inertia-driven regime ($Fr = 5$). The outermost curves form an envelope that captures the full variation due to these rheological differences. Within each regime, only the bulk rheological properties (internal friction, cohesion, and plastic compressibility) vary. Since the material parameter ranges are
175 identical across all cases (cf. Table 1), the spread of curves in each regime directly illustrates the effect of avalanche rheology on run-up height. Panel (b) in Fig. 3 is discussed at a later stage (Sect. 3.3). It presents a conceptually similar analysis to panel (a), but for a distinct quantity. We apply the same subfigure presentation in Fig. 3, Fig. 4, Fig. 7, and Fig. 10.

Curves of the gravity-driven case ($Fr = 0.1$) evolve smoothly toward a steady state, whereas curves of the transitional ($Fr = 1$) and inertia-driven cases ($Fr = 5$) exhibit initial peaks followed by the transition to steady conditions. These peaks originate from
180 the rapid upward ejection of material at first contact with the obstacle. Because this idealized scenario assumes a uniformly deep

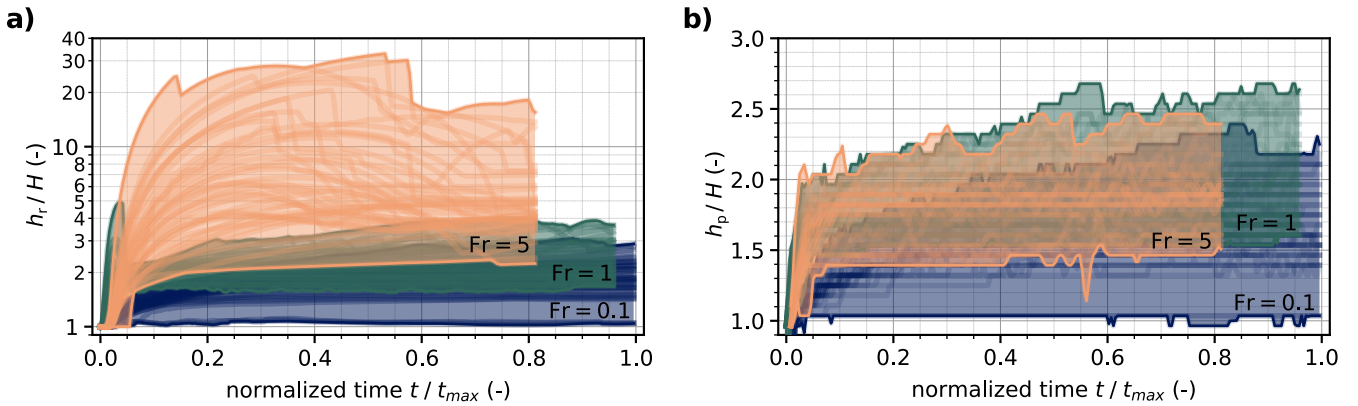


Figure 3. Envelopes of run-up height time histories (a) and pressure height (b) encompassing the whole range of varied material parameters (see Table 1) of a characteristic gravity-driven ($Fr = 0.1$ in blue), a transitional ($Fr = 1$ in green), and an inertia-driven regime ($Fr = 5$ in orange). The pronounced drops in the run-up time histories of $Fr = 5$ are sampling artifacts: as the highest ballistically ejected material point leaves the centered run-up height sampling domain (cf. Fig. 2), the reading falls discontinuously to the next-highest point inside it. Curves for $Fr = 1$ and $Fr = 5$ are clipped for better visualization.

flow with a vertical front, peak amplitudes may be sensitive to modeling simplifications; we therefore focus on steady-state run-up heights, which are more robust. Ratios of peak to mean steady-state run-up heights for all simulated cases are documented in Sect. S5 in the Supplements.

In the steady state, rheological variation has the strongest influence in the inertia-driven regime ($Fr = 5$): the corresponding envelope spans run-up heights from about 2 to over 30 times the initial flow height (i.e., a factor of approximately 15). At lower Fr the spreads are considerably smaller: a factor of about 3 for the gravity-driven case ($Fr = 0.1$) and a factor of 2.5 for the transitional case ($Fr = 1$). This contrasts with impact pressure buildup, where inertial effects outweigh rheology-related contributions in inertia-driven flows (Kyburz et al., 2020; Kohler et al., 2026a).

Analysis of the rheological-variation envelopes, however, does not isolate the contribution of individual rheological properties. In Fig. 4 (a), we achieve this through a virtual rheological decomposition, progressively introducing friction, cohesion, and plastic compressibility starting from an inviscid, fluid-like baseline, presented as stacked $\bar{h}_r(Fr)$ curves (similar to Kohler et al., 2026a; Kyburz et al., 2020).

The inviscid, fluid-like curve closely follows the velocity head augmented by the flow height, confirming that formulations based on Bernoulli's principle offer a reasonable first-order description of run-up on narrow obstacles. Introducing granular rheology has a twofold effect on run-up height. At low Fr , friction and cohesion increase run-up through quasi-static pile-up, in which stronger internal resistance supports a higher material accumulation at the obstacle (cf. Gravish et al., 2010); at high Fr , friction and cohesion increase energy dissipation during the conversion from kinetic to potential energy, thereby reducing run-up height. Plastic compressibility has a minor influence compared to friction and cohesion. Decomposition plots for other rheological parameters, confirming the representativeness of the selected ones, are provided in Sect. S6 in the Supplements.

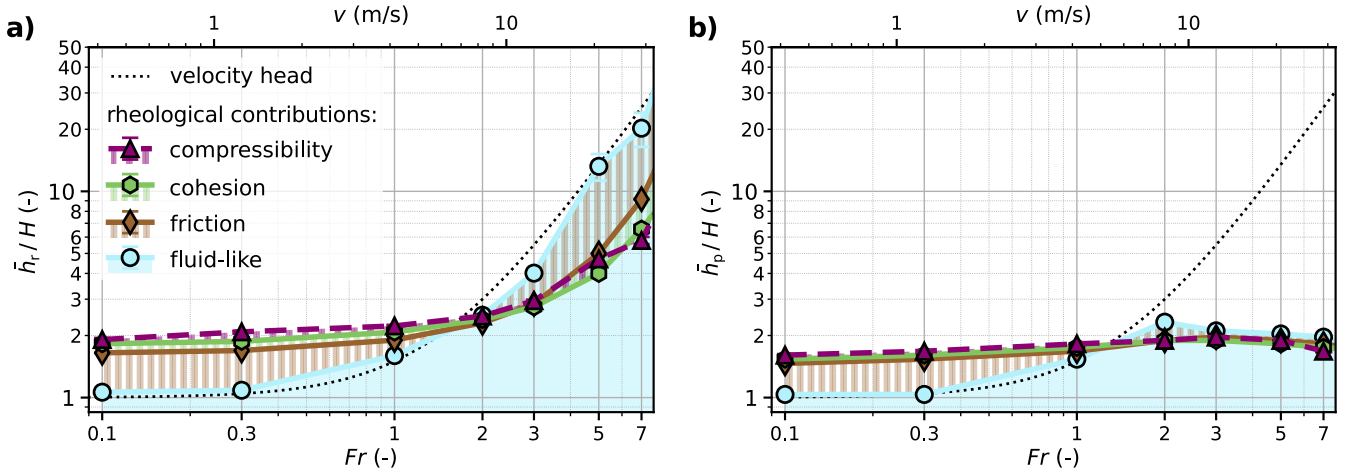


Figure 4. Run-up height (a) and pressure height (b) contributions from inviscid, fluid-like behavior, friction, cohesion, and plastic compressibility for $Fr = 0.1$ to 7. Starting with the simulation of inviscid, fluid-like flows ($M = 0.0$, $\beta = 0.0$, $\chi(p_c = 25) = 100.7\%$), we progressively modify the corresponding material parameters to incorporate frictional, cohesive-frictional, and finally compressible cohesive-frictional behavior. The final material properties are $M = 0.8$, $\beta = 0.3$, $\chi(p_c = 25) = 107.5\%$. The velocity head (augmented by the addition of the flow height) is shown for reference.

200 3.2 Impact pressure distribution and the concept of pressure height

In engineering practice, run-up height is commonly assumed to define the vertical extent of idealized impact pressure distributions on narrow obstacles. Our simulations show that this conflates two distinct quantities. Figure 5 compares two exemplary time-averaged profiles of impact pressure for identical rheological properties but contrasting flow regimes: gravity-driven and inertia-driven.

205 In the gravity-driven case (Fig. 5 (a), $Fr = 0.1$), significant pressure acts over a large fraction of the run-up height. In the inertia-driven case (Fig. 5 (b), $Fr = 5$), the pressure distribution is confined to a much smaller height compared to the run-up height. To precisely quantify the vertical extent of significant impact pressure, we introduce the *pressure height* h_p . We define h_p as the height above the gliding surface ($z = 0$) at which the smoothed impact pressure profile $\sigma_{xx}(z)$ falls below 5% of the depth-averaged impact pressure within the flow height, $\langle \sigma_{xx} \rangle_H$. Profiles are smoothed using a second-order Savitzky–Golay
 210 filter with a 13-bin window (corresponding to a window height of ≈ 1.5 m). Impact pressure profiles for other rheological parameters, confirming the representativeness of the selected ones, are provided in Sect. S7 in the Supplements.

Figure 6 generalizes this finding across the full parameter space. At low Froude numbers, pressure height and run-up height remain of comparable magnitude. Above $Fr \approx 2$, however, the two quantities diverge: while run-up continues to increase with Fr , pressure height saturates at approximately 1.5 to 2.5 H . This saturation is consistent with the laboratory observations of
 215 Hauksson et al. (2007) discussed in the introduction.

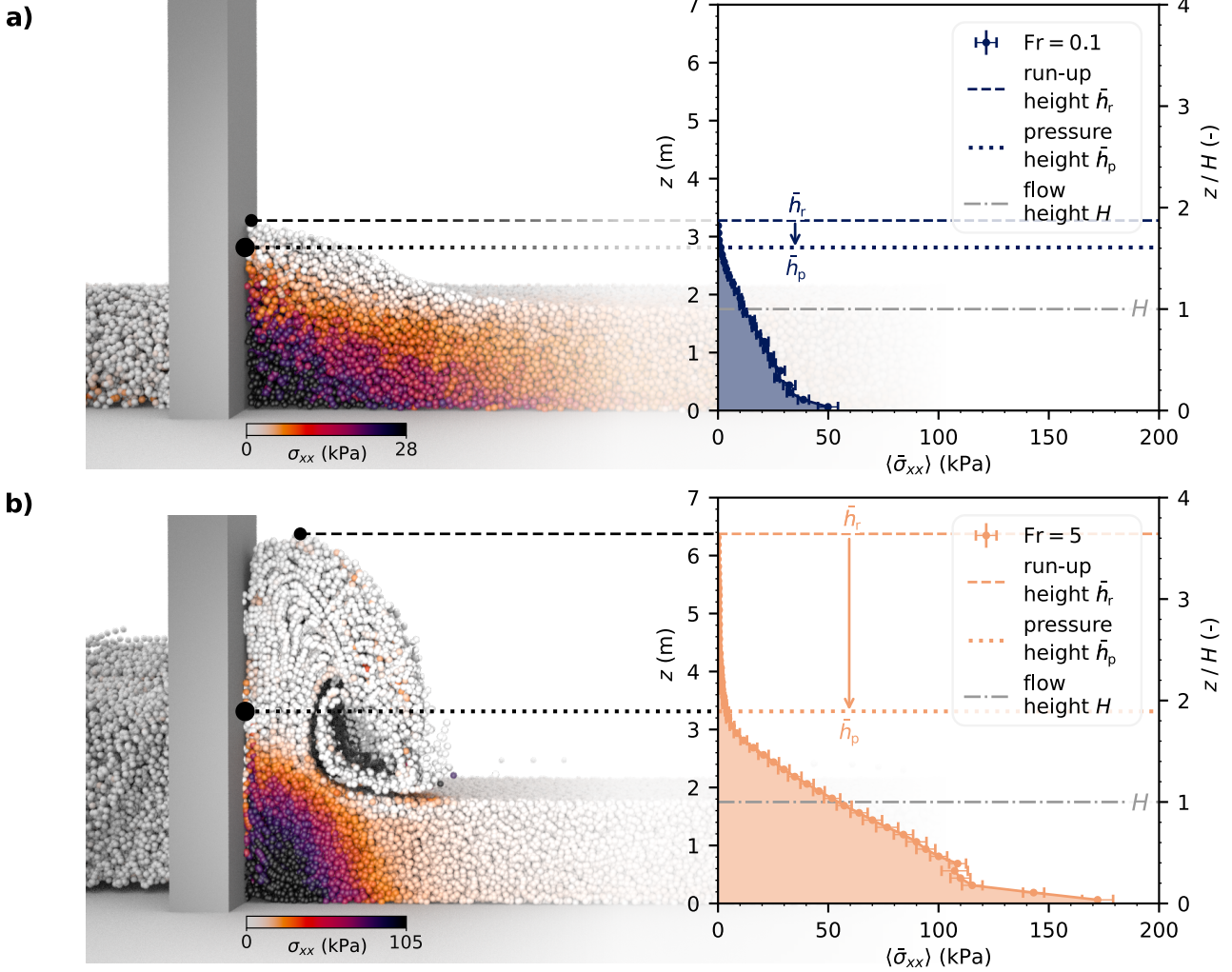


Figure 5. Longitudinal sections of two simulated avalanches (left) and the corresponding impact pressure profiles (right), highlighting the difference between run-up and pressure height. Material-Point colors indicate stream-wise stress σ_{xx} . Panel (a) shows a gravity-driven case ($Fr = 0.1$), and panel (b) an inertia-driven case ($Fr = 5$); both share identical avalanche rheology ($M = 0.8$, $\beta = 0.3$, $\chi(p_c = 25) = 107.5\%$).

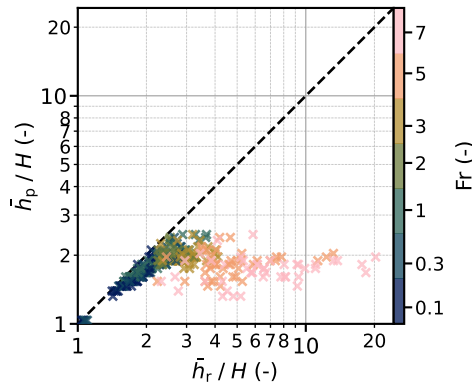


Figure 6. Pressure height over run-up height for the displayed Fr -range and the entire material parameter space constituted of M' and $\chi(p_c = 25)$.

Another observation from Fig. 5 is that both flow regimes show increasing pressure toward the obstacle base. This is noteworthy in the inertia-driven case, where a uniform velocity profile would suggest an approximately uniform pressure distribution, given the proportionality between impact pressure and velocity in this regime (Kyburz et al., 2020). We attribute this to material deflection at a dead zone, creating a local pressure concentration that grows toward the base. This is consistent with flume experiments on inertia-driven flows reporting profiles of similar shape during the initial jet-formation stage of impact (Armanini et al., 2011).

3.3 Pressure height and its rheological contributors

In direct analogy to Sect. 3.1, we examine how flow regime and avalanche rheology control pressure height, first through pressure height time series, then through isolation of rheological contributions for mean steady-state values, and finally by identifying the governing mechanisms.

The pressure height time series in Fig. 3 (b) show that avalanche rheology has a more uniform influence on pressure height across all flow regimes than it does on run-up height. In steady state, the envelopes remain of similar magnitude across Froude numbers, merely showing a baseline shift from $Fr = 0.1$ to the higher Froude numbers ($Fr = 1$ and $Fr = 5$). Unlike run-up, none of the curves exhibits pronounced transient peaks, regardless of flow regime or avalanche rheology (cf. Sect. S5 in the Supplements).

Applying the same virtual rheological decomposition as in Sect. 3.1 to obtain stacked $h_p(Fr)$ curves, we find that up to $Fr \approx 2$, pressure height behaves similarly to run-up height (cf. Fig. 4 (b)). The inviscid, fluid-like curve provides a baseline contribution, onto which frictional, cohesive, and plastic-compressibility effects add in a stacked manner. The influence of plastic compressibility is again minor compared to friction and cohesion. As for run-up height, we interpret this response as a quasi-static pile-up of material pushing against the obstacle. Beyond $Fr \approx 2$, however, pressure height saturates with Fr , indicating a fundamental change in the governing mechanisms.

For the inviscid, fluid-like case, lateral fluxes, inherent to the 3D nature of the present impact configuration, inhibit the formation of a persistent hydraulic jump, causing the pressure height to saturate. Under supercritical conditions, the incoming flow forms a vertical jet upon collision with the obstacle. For sufficiently wide obstacles, continued material accumulation ahead of the obstacle transforms the jet into a hydraulic jump (Armanini et al., 2011; Wu et al., 2023) that pushes statically against the obstacle, making pressure height equal to run-up height. For narrow obstacles, however, lateral fluxes inhibit this jump. The interaction remains deflection-driven, with particles deflected upward, losing streamwise velocity. Once that velocity approaches zero, momentum transfer to the obstacle diminishes while material continues to rise. Pressure height, therefore, saturates while run-up does not.

For granular rheologies, Fig. 4 (b) shows that pressure height becomes nearly independent of velocity, pointing to another mechanism. We attribute this to dead-zone formation, a classical feature of granular impact that develops largely independently of flow velocity (Gray et al., 2003). At narrow, blunt obstacles, dead zones adopt wedge-shaped geometries (Tregaskis et al., 2022; Thibert et al., 2008), creating an internal interface between moving and static material where flow deflection occurs, and impact pressures concentrate. The formation, shape, and persistence of the dead zone are controlled by granular rheology rather than velocity, which explains the observed velocity independence of pressure height. We further expect this mechanism to depend strongly on obstacle geometry, particularly the relative width w/H , as wider obstacles reduce lateral fluxes and sustain larger dead zones.

Together, these findings indicate that dead-zone formation and associated flow deflection govern pressure height on narrow obstacles, producing a behavior fundamentally different from run-up. Treating the two quantities as equivalent lacks physical justification, particularly in inertia-driven regimes.

4 Semi-empirical estimation of run-up and pressure height in avalanches

These physical distinctions motivate separate semi-empirical expressions for run-up and pressure height, each reflecting its governing mechanism. We stay in line with the guideline formulation by adopting the velocity head together with a dissipation factor λ as the basis of the inertia-driven contribution, and by keeping a width-correction factor $f(w/H)$. We depart from it in two respects: we propose an additive decomposition in which a quasi-static term is added to the inertia-driven contribution, and we replace the dichotomy between dry, loose snow avalanches and dense snow avalanches with a continuous rheology-dependent parametrization. Rather than reproducing the full complexity of the 3D simulations, we aim to retain the dominant trends in a form suitable for engineering use.

The guideline formulation for run-up height goes back to Salm et al. (1990), who formalized the velocity head from Bernoulli's principle, Eq. (1), by introducing an empirical energy dissipation factor λ and a width-correction factor $f(\frac{w}{H})$, yielding the expression

$$h_r = \frac{h_v}{\lambda} f\left(\frac{w}{H}\right) = \frac{v^2}{2g\lambda} f\left(\frac{w}{H}\right). \quad (5)$$

The dissipation factor λ depends on avalanche type, and $f\left(\frac{w}{H}\right)$ accounts for the obstacle width w relative to the incoming flow height H . The guidelines consistently prescribe $\lambda = 1.5$ for dry, loose snow avalanches and $\lambda = 2$ to 3 for dense snow
270 avalanches. The width-correction factor is given in tabular form and is well approximated by

$$f\left(\frac{w}{H}\right) = 1 - \exp\left(-1.14 \frac{w}{H}\right). \quad (6)$$

4.1 Semi-empirical modeling of run-up and pressure height

Both run-up and pressure height arise from the superposition of a gravity-driven pile-up and an inertia-driven contribution, motivating the additive decomposition

$$275 \quad \bar{h}_i = \bar{h}_{i,\text{gr}} + \bar{h}_{i,\text{in}}, \quad (7)$$

where the index $i \in \{\text{r}, \text{p}\}$ distinguishes between run-up (r) and pressure height (p). The linear regressions of Huber et al. (2021), adopted in ÖNORM B 4801 (2024), also yield a velocity-independent offset, further supporting an additive decomposition of run-up height.

We model the gravity-driven pile-up process identically for both quantities using the linear model

$$280 \quad h_{i,\text{gr}} = H(1 + \zeta_i) \quad \text{with} \quad \zeta_i = k_i M'. \quad (8)$$

The factor ζ_i quantifies the quasi-static pile-up process due to internal resistance. We model this effect solely through the effective internal friction M' ; plastic compressibility is omitted for simplicity. The fitting parameter k_i controls the proportionality between M' and ζ_i for run-up and pressure height, respectively. For inviscid, fluid-like material behavior ($M' = 0$), Eq. (8) reduces to $h_{i,\text{gr}} = H$ (i.e., $\zeta_i = 0$), consistent with experimental observations that subcritical water flows produce negligible
285 run-up (Choi et al., 2015).

For the inertia-driven term, both run-up and pressure height follow the velocity head at low to moderate Fr. Run-up continues to scale with the velocity head at high Fr, whereas pressure height saturates beyond a characteristic Froude number (cf. Sect. 3.2). We capture this saturation by limiting the velocity head to a height threshold

$$h_{\text{sat}} = \frac{\text{Fr}_{\text{sat}}^2 H}{2}, \quad (9)$$

290 computed from the fitted Froude number at saturation Fr_{sat} . Here we use Eq. (1) and $\text{Fr} = v/\sqrt{gH}$. The inertia-driven contributions are then written as

$$\bar{h}_{i,\text{in}} = \begin{cases} \frac{h_v}{\lambda_i}, & \text{if } i = \text{r}, \\ \frac{\min(h_v, h_{\text{sat}})}{\lambda_i}, & \text{if } i = \text{p}, \end{cases} \quad \text{with } \lambda_i = \exp(\kappa_i M'). \quad (10)$$

In direct analogy to Eq. (5), the factors λ_i represent energy dissipation factors. We model these factors as increasing exponentially with the effective internal friction M' , with the rate controlled by the parameter κ_i . The exponential form empirically matches the

295 $h_i - M'$ trends presented in Sect. S8 in the Supplements, and ensures $\lambda_i = 1$ for $M' = 0$, corresponding to the inviscid, fluid-like limit, while smoothly introducing friction-dependent dissipation for $M' > 0$. This replaces the avalanche-type classifications of Salm et al. (1990) with a continuous rheology-based parametrization.

Table 3. Regression coefficients for the run-up height and pressure height equation.

(a) Run-up height equation.		(b) Pressure height equation.		
k_r (-)	κ_r (-)	k_p (-)	κ_p (-)	Fr_{sat} (-)
0.95	1.57	0.53	1.31	1.54
RMSLE = 13.0 %		NRMSE = 6.6 %		

We determine the regression parameters using the `scipy.optimize.curve_fit` routine (Virtanen et al., 2020). The four-parameter dataset comprises the effective internal friction M' , the plastic compressibility $\chi(p_c = 25)$, the flow velocity v , and the steady-state run-up $\bar{h}_r$ or pressure height $\bar{h}_p$, spanning the parameter ranges stated in Table 1 and Table 2, except for $\chi(p_c = 25) = 205.3\%$. Details on the derivation of the regression parameters and further performance metrics are reported in Sect. S8 in the Supplements. We assess the run-up model using the root mean square logarithmic error (RMSLE), given the quadratic velocity dependence of run-up height, and the pressure height model using the normalized root mean square error (NRMSE). Figure 7 visualizes overall model performance. Both equations perform best for low to moderate plastic

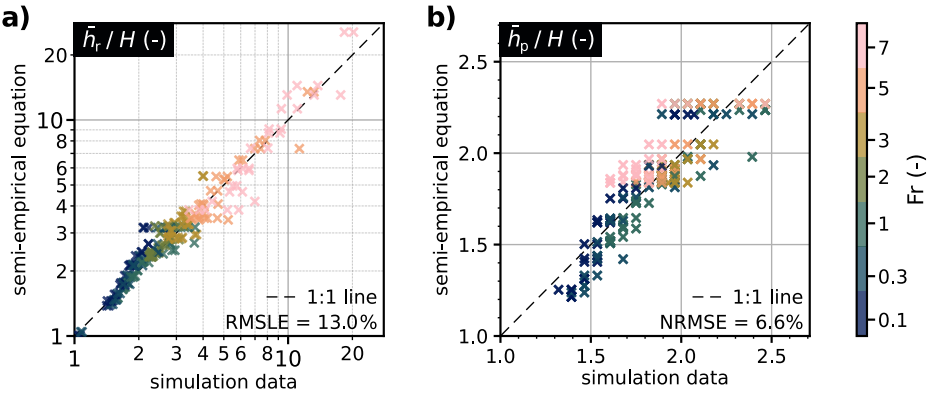


Figure 7. Semi-empirical equation for run-up height (a) and pressure height (b) vs. simulation results for the displayed Fr -range, spanning all simulated M' and $\chi(p_c = 25)$ values except $\chi(p_c = 25) = 205.3\%$.

305 compressibilities. The run-up height equation shows slightly improved accuracy for intermediate effective internal friction ($M' \approx 0.4$ to 1.5); the accuracy of the pressure height equation shows no systematic dependence on M' . Across the full dataset, 92.9% of simulated data points are predicted within $\pm 25\%$ by the run-up height equation; the pressure height equation captures

100% of the data within the same tolerance band. These values are drawn from a more detailed evaluation of the model performance, included in Sect. S8 in the Supplements.

310 The resulting $\zeta_i(M')$ and $\lambda_i(M')$ curves are shown in Fig. 8, with left ordinates giving the run-up height coefficients ζ_r and λ_r and right ordinates giving the pressure height coefficients ζ_p and λ_p .

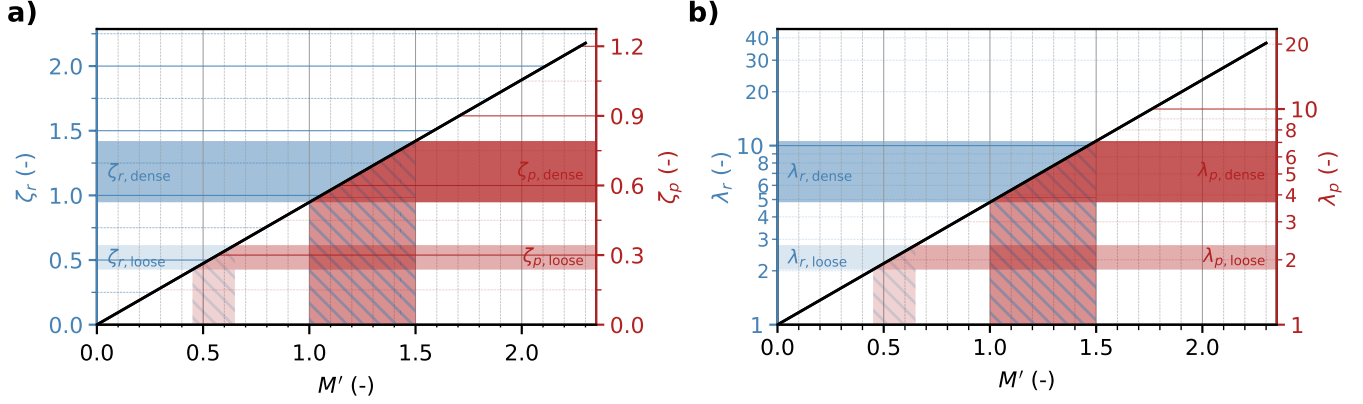


Figure 8. Quasi-static magnification factors ζ_r and ζ_p (a), and dissipation factors λ_r and λ_p (b) for run-up and pressure height, respectively, over the effective internal friction M' . The hatched areas mark the recommended value range for M' to match the run-up height of loose and dense snow avalanches from the guidelines. Note the different ordinate scalings.

4.2 Identification of rheological parameters

The introduction of the dissipation factor λ in Eq. (5) and its value range are mostly grounded in engineering judgment. Nevertheless, decades of application suggest that the formulation gives a reasonable first-order description of run-up height for the prescribed λ values. We exploit this by identifying the values of M' for which our simulated run-up curves best match the guideline predictions (Eq. (5)), effectively translating λ into the physically meaningful parameter space of M' . This further allows established engineering knowledge for run-up estimation to be transferred to the pressure–height formulation proposed here.

320 To this end, we compare simulated $\bar{h}_r$ –Fr curves for all considered avalanche rheologies against those computed from the guidelines, restricting the analysis to the inertia-driven regime ($3 \leq \text{Fr} \leq 7$), since Eq. (5) lacks a contribution from quasi-static pile-up. We quantify deviations between the simulated and guideline curves using the RMSLE as a function of M' .

The resulting RMSLE– M' curves are shown in Fig. 9 for both dry, loose snow avalanches and dense snow avalanches. In both cases, distinct minima indicate clear correspondences between the suggested values for the dissipation factor λ and physically meaningful ranges of M' within our numerical framework. The correspondence is consistent for both nearly incompressible and moderately compressible configurations. For dry, loose snow avalanches ($\lambda = 1.5$), the best agreement occurs for $M' \approx 0.45$ to 0.65 . Dense snow avalanches ($\lambda = 3$) correspond to higher friction levels, with $M' \approx 1.0$ to 1.5 . These parameter ranges are marked in Fig. 8.

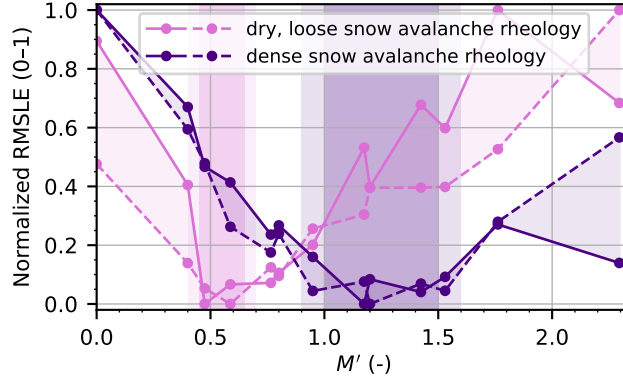


Figure 9. Deviation between simulated run-up height and the run-up height predicted by the guidelines (Eq. (5)) for *dry, loose* and *dense* avalanche rheology (using $\lambda = 1.5$ and 3 , respectively), plotted against the effective internal friction M' . The deviation is quantified using the RMSLE for each M' , evaluated only for the inertia-driven regime ($3 \leq Fr \leq 7$). The resulting RMSLE - M' curves are normalized to 0-1 to enable direct qualitative comparison. Continuous lines correspond to a nearly incompressible configuration ($\chi(p_c = 25) = 100.7\%$), whereas dashed lines represent a moderately compressible configuration ($\chi(p_c = 25) = 107.5\%$). Each avalanche rheology reveals a clear correspondence between the recommended values of the empirical dissipation factor λ and a range of M' of the MPM model.

4.3 Influence of relative obstacle width

The width-correction factor $f(\frac{w}{H})$ reduces predicted run-up height for obstacles that are narrow relative to the flow height. We assess its validity within our numerical framework and test whether obstacle width affects run-up and pressure height similarly, using the rheological parameter ranges identified in Sect. 4.2 for dry, loose snow avalanches and dense snow avalanches.

For dry, loose snow avalanches, we use $M = 0.5$ and $\beta = 0.15$ (resulting in $M' = 0.59$) with $\chi(p_c = 25) = 107.5\%$, corresponding to moderate plastic compaction potential. For dense snow avalanches, we use $M = 0.9$ and $\beta = 0.3$ (resulting in $M' = 1.32$) with $\chi(p_c = 25) = 102.4\%$, corresponding to small plastic compaction potential. In both cases, we vary the relative obstacle width over $w/H \in \{0.5, 1, 2, 3\}$. To sufficiently resolve narrow obstacles, we reduce the grid spacing to $dx = 0.125$ m. A sensitivity analysis confirms robustness with respect to grid resolution (cf. Sect. S2 in the Supplements).

Similar to the width-correction factor in Eq. (5), we compute for each Fr

$$f_i\left(\frac{w}{H}\right) = \frac{\bar{h}_i\left(\frac{w}{H}\right)}{\bar{h}_i\left(\frac{w}{H} = 1\right)}, \quad (11)$$

which can be interpreted as a width-correction factor for run-up ($i = r$) and pressure height ($i = p$), relative to the reference case $w/H = 1$. Note that this definition differs from that in the guidelines, where the reference case corresponds to $w/H \geq 3$. We therefore rescale Eq. (6) such that it satisfies $f(\frac{w}{H}) = 1$ at $w/H = 1$.

Run-up height is only weakly sensitive to obstacle width across both avalanche types, with slightly more pronounced dependence for dense snow rheology (cf. Fig. 10, panels a.1 and a.2). Overall, the width correction proposed in the guidelines overestimates run-up height for $w/H > 1$ and underestimates it for $w/H < 1$.

dry, loose snow avalanche rheology:

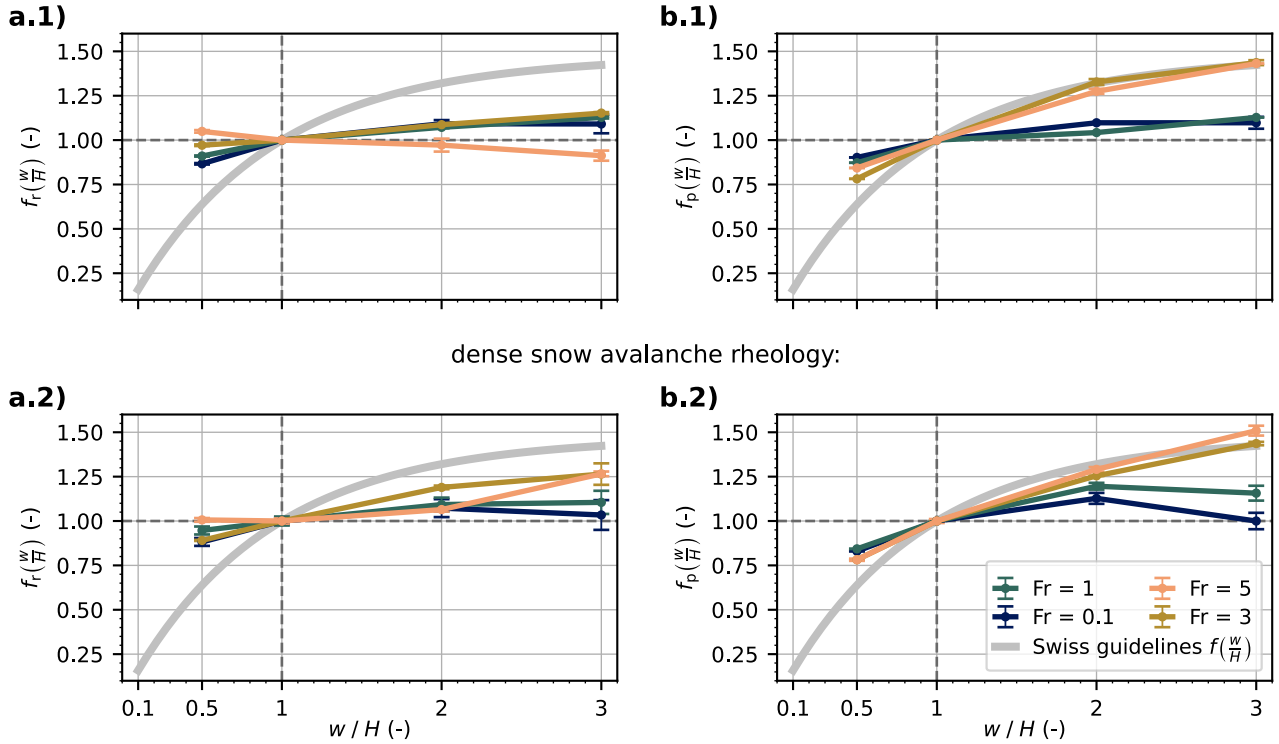


Figure 10. Width-correction factors $f_i(\frac{w}{H})$ for run-up height ($i = r$, left column) and for pressure height ($i = p$, right column) plotted over the normalized obstacle width w/H . The upper row (panels a.1 and b.1) corresponds to dry, loose snow avalanche rheology ($\chi(p_c = 25) = 107.5\%$, $M = 0.5$, $\beta = 0.15$; $M' = 0.59$), and the lower row (panels a.2 and b.2) corresponds to dense snow avalanche rheology ($\chi(p_c = 25) = 102.4\%$, $M = 0.9$, $\beta = 0.3$; $M' = 1.32$), following Sect. 4.2.

345 Pressure height is more sensitive to obstacle width, particularly in inertia-driven regimes ($Fr = 3$ and $Fr = 5$), where the numerical results closely follow the equation proposed in the guidelines (cf. Fig. 10, panels b.1 and b.2). In gravity-driven ($Fr = 0.1$) and transitional ($Fr = 1$) regimes, the width dependence is substantially weaker. As for run-up height, the width correction proposed in the guidelines underestimates pressure height for $w/H < 1$.

For obstacles wider than the flow height ($w/H > 1$), the guidelines width correction is adequate: conservative for run-up
 350 height and accurate for pressure height. For narrower obstacles ($w/H < 1$), however, the simulations do not support the degree of reduction permitted by the guidelines. This is particularly relevant for slender structures such as cableway masts and transmission towers, where $w/H < 1$ is common.

5 Conclusions

This study examined the run-up and impact pressure distribution of snow avalanches impacting narrow obstacles, with two aims:
355 clarifying the underlying physical mechanisms and improving their representation in avalanche engineering guidelines. We addressed both through a comprehensive three-dimensional numerical study using MPM, systematically varying avalanche velocity and rheology.

Avalanche run-up on narrow obstacles can be quantified reasonably well by formulations based on the velocity head from Bernoulli's principle, provided that (i) a rheology-dependent gravity-driven term is included and (ii) energy dissipation is
360 quantified through rheological properties. Friction and cohesion increase quasi-static pile-up in gravity-driven regimes but act dissipatively at higher Froude numbers, reducing inertia-driven run-up. Building on these trends, we proposed semi-empirical extensions of the velocity-head formulation used in the guidelines, continuously parameterized through the effective internal friction. Within this framework, the empirical avalanche-type dependent dissipation factors prescribed in the guidelines map systematically to distinct ranges of effective internal friction in our constitutive model. These are $M' \approx 0.45$ to 0.65 for dry,
365 loose snow avalanches and $M' \approx 1.0$ to 1.5 for dense snow avalanches.

A central finding is that run-up height is not a reliable indicator of the vertical extent of significant impact pressure, particularly in inertia-driven regimes. While run-up may reach several flow heights, significant impact pressure remains confined to a much smaller extent, typically a few flow heights. We introduced pressure height as a distinct measure of this effective load height. Unlike run-up, pressure height is primarily controlled by flow deflection at a dead zone near the obstacle base. This process is
370 governed by avalanche rheology rather than flow velocity. Even for inviscid, fluid-like rheology, pressure height saturates at a characteristic Froude number, marking the onset of supercritical conditions. For practical application of these findings, assuming a maximum pressure height of approximately three flow heights provides a conservative approximation, consistent with the experimental observations of Hauksson et al. (2007).

Width effects are most pronounced for pressure height in inertia-driven regimes and negligible in gravity-driven regimes. The
375 width-correction factor adopted in the guidelines is adequate for obstacles wider than the flow height. For narrower obstacles, the configuration typical of cableway masts and transmission towers, our results do not support the magnitude of reduction prescribed by the guidelines for either run-up or pressure height, and we recommend limiting $f(\frac{w}{H})$ to a minimum of 0.7 for $w/H < 1$. Referenced to $w/H = 1$, as in Fig. 10, this corresponds to holding $f(\frac{w}{H})$ at unity.

In Appendix A, we apply the proposed pressure height formulation to the avalanche impact calculation example of Jóhannesson et al. (2009, Section E.2) and compare the resulting base shear and base moment with the load models of Jóhannesson et al. (2009) and those from the Swiss guidelines (Margreth et al., 2015). The proposed approach does not systematically raise or
380 lower the design actions, but redistributes them: in fast conditions, at $v = 30 \text{ m s}^{-1}$, it gives base actions up to 28% below the two references. In slow conditions, at $v = 10 \text{ m s}^{-1}$, however, it exceeds the base actions calculated following the Swiss guidelines by 15% to 25% , because the pressure height features a velocity-independent contribution.

385 This study builds on several simplifying assumptions that limit its scope. The analysis is restricted to plug flow velocity profiles, whereas many avalanche flow regimes exhibit pronounced shear (Köhler et al., 2018). Only dense, granular snow

avalanches are considered; effects related to powder snow avalanches are beyond the scope of this work. The constitutive model has neither thermo-mechanical coupling nor a liquid water phase, so temperature and liquid water content enter only through their effect on the bulk rheological parameters. The study is further confined to steady conditions, yet temporal variability in
390 flow height, velocity, or density is a principal source of uncertainty in avalanche impact (Jóhannesson et al., 2009).

Taken together, these assumptions delimit the conditions under which we have the highest confidence in the proposed formulations:

- dense, cohesive-frictional flow at approximately steady conditions (cf. Sect. S8 in the Supplements),
- plug-like velocity profiles, at velocities up to about 30 m s^{-1} ,
- 395 – obstacles with rectangular cross sections and relative widths of $w/H = 0.5$ to 3 ,
- approximately constant temperature and liquid water content at the instant of impact.

The raised limitations point directly to the most pressing directions for future work. Extending the framework to sheared or unsteady inflow conditions would remove the two most restrictive assumptions. A dedicated geometrical parametric study, varying obstacle width, flow height, and cross-sectional shape independently, could clarify the role of flow height and test the
400 universality of Froude number scaling. Such a study, extending and building on the analysis of Huber et al. (2021), would also provide the empirical basis needed to derive shape-dependent correction factors for run-up, similar to the drag coefficients used for impact pressure estimation (Jóhannesson et al., 2009). Transient peak run-up and the vertical loading on protruding structural elements also offer promising ground for numerical and experimental investigation.

The proposed formulations, despite being grounded in systematic rheological analysis, remain semi-empirical; a closed
405 analytical treatment appears difficult to achieve for spatial impact problems. Semi-empirical approaches supplemented by three-dimensional simulations, however, offer a pragmatic path toward more general methods.

Code and data availability. The main raw time-series data, a postprocessing script reproducing the key figures, and the regression of the equations are publicly available in a Zenodo repository (Kohler et al., 2026b).

Author contributions. Michael J. Kohler: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis,
410 Data curation, Conceptualization. Johan Gaume: Writing – review & editing, Validation, Supervision, Software, Methodology, Investigation, Conceptualization. Christophe Ancey: Writing – review & editing, Supervision. Betty Sovilla: Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Competing interests. The authors declare that they have no conflict of interest.

Acknowledgements. During the preparation of this manuscript, the authors used large language models (ChatGPT and Claude) and DeepL to assist with improving language and readability. All content generated or modified using these tools was carefully reviewed and edited by the authors, who take full responsibility for the final manuscript. No AI tools were used for the interpretation of the results or for drawing scientific conclusions.

Appendix A: Calculation example and comparison with guidelines

Jóhannesson et al. (2009, Section E.2), henceforth referred to as the *EC handbook*, presents a worked calculation example of an avalanche impacting a circular mast (Table A1, original scenario). A front velocity of 30 m s^{-1} places this design avalanche between a fast dry, loose snow avalanche and a mixed powder snow avalanche (PSA) (Rudolf-Miklau et al., 2014). The *EC handbook* therefore compares its mixed PSA load model with the dense flow load model of the Swiss guidelines (Margreth et al., 2015), which is defensible for a scenario situated between the two regimes. We also apply our proposed pressure height concept to this example, noting that this article mainly concerns dense flows and that the original example scenario thus sits at the margin of its applicability. We nevertheless evaluate the original scenario first, because it is a published and familiar reference case.

Table A1. Example scenario: avalanche impact on a circular mast (taken from Jóhannesson et al., 2009).

Symbol	Description	Value
w	mast diameter	1.5 m
H	avalanche depth	2.0 m
ρ	avalanche density	300 kg m^{-3}
H_s	snow cover depth	1.5 m
l_{track}	track length	900 m
C_D	dense drag coefficient (cylindrical mast)	1.5
original scenario:		
v	front velocity	30 m s^{-1}
$C_D \rho v^2 / 2$	dynamic dense impact pressure	203 kPa
modified scenario:		
v	front velocity	10 m s^{-1}
$C_D \rho v^2 / 2$	dynamic dense impact pressure	22.5 kPa

We subsequently present a second calculation in which we reduce the front velocity of the design avalanche to 10 m s^{-1} , placing the scenario in the dense regime our approach mainly addresses (Table A1, modified scenario). The *EC handbook* gives no load model for purely dense avalanche impact but refers to the Swiss guidelines; we therefore compare our approach to the Swiss guidelines alone in this second scenario.

For comparability between the approaches, and to remain consistent with the *EC handbook*, we apply the same dynamic pressure within the dense flow depth in all approaches in both scenarios; they differ only in how they distribute the load above

and below it. We note, however, that especially in the slower modified scenario, an impact pressure estimate accounting for gravitational pressure may be more appropriate (e.g., Kyburz et al., 2022). In both scenarios, the rheological parameter of our approach and the dissipation factor of the Swiss guidelines are chosen consistently with the correspondence established in
435 Sect. 4.2.

A1 Original scenario

The Swiss guidelines distribute the dynamic avalanche pressure uniformly over the flow depth and let it decrease linearly to zero over the run-up height, $h_r = v^2 / (2g\lambda) f(\frac{w}{H}) = 17.6 \text{ m}$, with $\lambda = 1.5$ and $f(\frac{w}{H}) = 0.57$ for $w/H = 0.75$ (following our continuous approximation, Eq. (6)). We adopt the dissipation factor λ recommended for dry, loose avalanches (Margreth et al.,
440 2015), whereas the *EC handbook* applies $\lambda = 2.5$ in this example. Since the run-up height is measured from the flow surface, the load would extend to 21.1 m above the ground. For fluidized avalanches ($v > 28 \text{ m s}^{-1}$) the Swiss guidelines (Margreth et al., 2015) propose limiting the run-up height to $v / (10 \text{ s}^{-1})$, referring explicitly to the rules of the *EC handbook*. Applying this limit, $h_r = v / 10 \text{ s}^{-1} = 3.0 \text{ m}$, the load extends to only 6.5 m above the ground.

The mixed PSA load model of the *EC handbook* also holds the dynamic pressure constant over the dense flow depth. It adopts
445 a drag coefficient of $C_D = 1.5$ within the dense flow and in the snow cover, whereas $C_D = 1$ is prescribed for the fluidized layer and the powder part above the dense flow. Below the dense flow, the model accounts for stress transmission through the snow cover and assumes a linear decrease to zero at ground level. Above the dense flow, the dynamic pressure decreases linearly over the assumed thickness of the fluidized layer, $v / 10 \text{ s}^{-1} = 3.0 \text{ m}$, but not to zero: it drops to the pressure assumed for a fluidized layer, $q_H = \rho_H v^2 / 2 = 6.75 \text{ kPa}$ with $\rho_H = 15 \text{ kg m}^{-3}$. The powder cloud extends above the fluidized layer, and
450 its thickness grows with the distance traveled along the avalanche track, $h_{\text{pow}} = 1 \times 10^{-5} \text{ s}^2 \text{ m}^{-2} l_{\text{track}} v^2 = 8.1 \text{ m}$. Over this thickness, q_H decreases following a power law to zero at the top of the powder cloud, 14.6 m above the ground (Eq. (12.31) in the *EC handbook*); we adopt an exponent of one, hence a linear decrease. The jump in the load profile at the flow surface in Fig. A1 arises from the change in C_D between the dense and the fluidized layer.

Like the reference method from the Swiss guidelines, used in the original example from the *EC handbook*, our approach does
455 not account for loading caused by a fluidized layer or a powder part and mainly concerns dense avalanche impact. Instead of the run-up height, we use the pressure height as a dedicated load distribution parameter (cf. Table 3 for the following). For the present dry, loose flow, we assume $M' = 0.65$, which corresponds to $\varphi' = 17^\circ$ (Fig. 1). The gravity-driven (i.e., velocity-independent) part of the pressure height then follows as

$$h_{p,\text{gr}} = H(1 + \zeta_p) = 2.7 \text{ m} \quad \text{with} \quad \zeta_p = 0.53 M' = 0.35. \quad (\text{A1})$$

460 For the inertia-driven part, we first compute the saturation height for the given flow height

$$h_{\text{sat}} = \frac{\text{Fr}_{\text{sat}}^2 H}{2} = 2.4 \text{ m} \quad \text{with} \quad \text{Fr}_{\text{sat}} = 1.54, \quad (\text{A2})$$

from which the inertia-driven pressure height follows as

$$h_{p,\text{in}} = \min\left(h_{\text{sat}}, \frac{v^2}{2g}\right) / \lambda_p = 1.0 \text{ m} \quad \text{with} \quad \lambda_p = \exp(1.31 M') = 2.34. \quad (\text{A3})$$

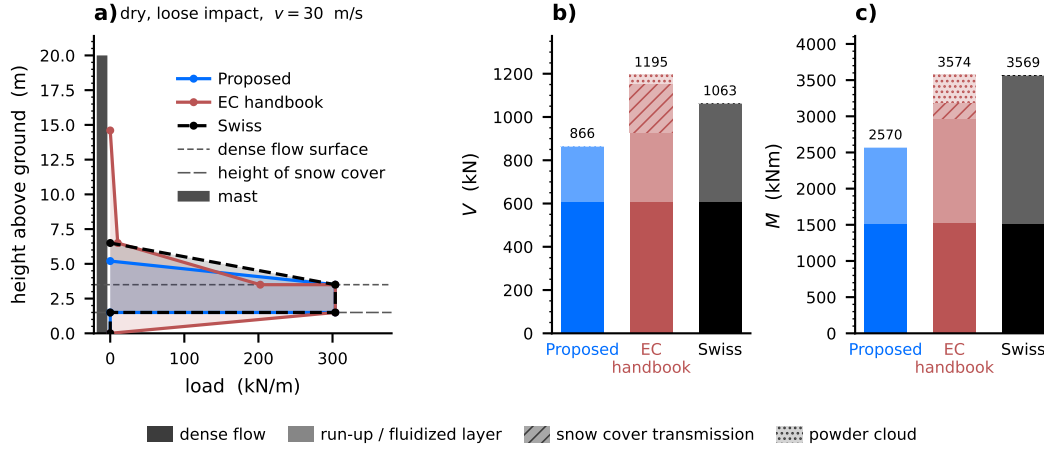


Figure A1. Line-load distributions over height (a) and the base shear (b) and base moment (c) they integrate to, for the mast of the *EC handbook* example at $v = 30 \text{ m s}^{-1}$. The bars are split into the parts of the load they integrate; all three approaches share the dense flow contribution and differ in what they add around it. The *EC handbook* is the only approach that considers loads from the snow cover, a fluidized layer and a powder part, and that changes C_D at the flow surface, hence the jump in its profile.

The obstacle width relative to the flow depth enters through

$$465 \quad f_p\left(\frac{w}{H}\right) = \frac{\max\left(1 - \exp\left(-1.14 \frac{w}{H}\right), f_{p,1}\right)}{f_{p,1}} = 1.00 \quad \text{with} \quad f_{p,1} = 1 - \exp(-1.14 \cdot 1) = 0.68, \quad (\text{A4})$$

that is, through the same width function as in Margreth et al. (2015), normalized to its value at $w/H = 1$ and capped there. Consequently, we set $f_p(w/H) = 1$ for every obstacle narrower than the flow is deep, as in the present example with $w/H = 0.75$. Expressed against the reference width of the guidelines ($w/H \geq 3$), this cap corresponds to the recommended minimum of $f(w/H) \approx 0.7$ stated in Sect. 5, since $f_{p,1} = 0.68$. The pressure height then follows as

$$470 \quad h_p = (h_{p,\text{gr}} + h_{p,\text{in}}) f_p\left(\frac{w}{H}\right) = 3.7 \text{ m}, \quad (\text{A5})$$

measured from the base of the flow, so that the load extends to 5.2 m above the ground.

Figure A1 shows the resulting load distributions together with the base shear V and the base moment M they integrate to. The Swiss guidelines, with the run-up height limited to $v/(10 \text{ s}^{-1})$, give $V = 1063 \text{ kN}$ and $M = 3569 \text{ kNm}$. The *EC handbook* gives a comparable base moment, $M = 3574 \text{ kNm}$, but a 12 % larger base shear, $V = 1195 \text{ kN}$. This is mainly due to the force
475 transmitted through the snow cover (228 kN) and the powder part (41 kN), which overcompensate the smaller load applied in the fluidization zone (319 kN compared to the 456 kN within the run-up height of the Swiss guidelines). Our approach gives the smallest reaction forces, $V = 866 \text{ kN}$ and $M = 2570 \text{ kNm}$, corresponding to -19% and -28% relative to the Swiss guidelines, and to -28% in both quantities relative to the *EC handbook*. The difference is larger for the base moment than for the base shear, because all three approaches share the load within the flow depth and differ only in its distribution above and below,
480 which shifts the points of application of the corresponding force resultants.

A2 Modified scenario

We now consider a dense flow impacting the same mast at a front velocity of $v = 10 \text{ m s}^{-1}$, leaving all other parameters of Table A1 unchanged. At this velocity, the run-up height is no longer limited to $v/(10 \text{ s}^{-1})$ according to the Swiss guidelines, but is evaluated at its full value, $h_r = v^2/(2g\lambda) f(\frac{w}{H}) = 0.98 \text{ m}$, using $\lambda = 3$, the value recommended for dense avalanches (Margreth et al., 2015). Correspondingly, we set $M' = 1.2$ ($\equiv \varphi' = 30^\circ$) in our approach, from which the pressure height amounts to $h_p = 3.8 \text{ m}$, measured from the bottom of the flow depth.

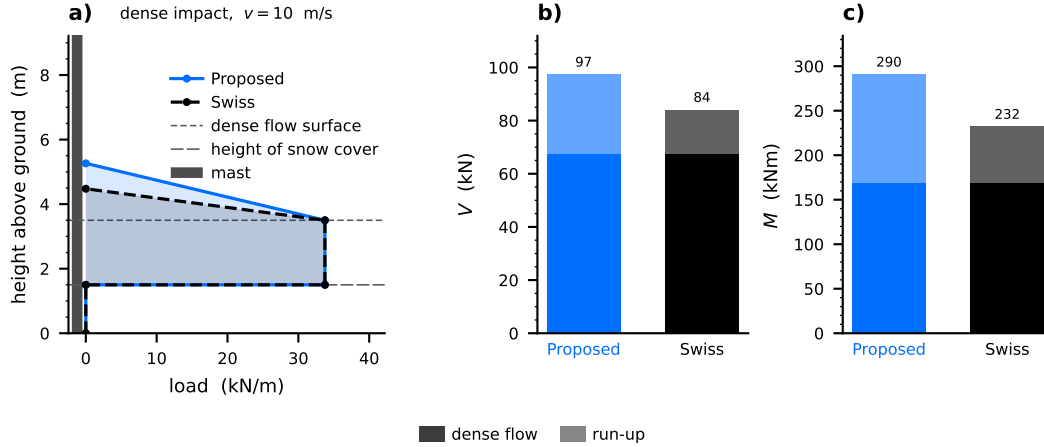


Figure A2. As Fig. A1, but for the same mast impacted by a dense flow at $v = 10 \text{ m s}^{-1}$, and comparing the proposed approach to the Swiss guidelines only.

Figure A2 shows that the ranking of the two approaches reverses in this regime. The Swiss guidelines now give the smaller reaction forces, $V = 84 \text{ kN}$ and $M = 232 \text{ kNm}$, because their load distribution proxy, the run-up height, scales purely with v^2 and has become small. Our approach gives $V = 97 \text{ kN}$ and $M = 290 \text{ kNm}$, that is, 15 % and 25 % above the base reactions computed from the Swiss guidelines. At this velocity, the pressure height is dominated by its gravity-driven part, which scales with M' and the flow height rather than with velocity.

Both scenarios shown here are single points of an approximate velocity range empirically representative of the given avalanche regime. To increase the generality of the findings, we repeat each regime comparison over its typical velocity range (Rudolf-Miklau et al., 2014), holding the remaining inputs at the values of Table A1. The two sweeps are given in Sect. S9 in the Supplements and support the reading above.

In summary, the main advantage of the proposed approach is not that it lowers or raises the design actions relative to the guidelines. Rather, it lies in the fact that the pressure height physically better reflects the loading of a dense avalanche on a narrow obstacle: it combines an inertia-driven part, which saturates under supercritical conditions (beyond $\text{Fr}_{\text{sat}} \approx 1.5$), with a gravity-driven part, which scales with the flow depth and persists at low velocities. Concepts of the *EC handbook* can be combined with this framework, in particular the stress transmission through the snow cover, which we consider physically

justified and which contributes 228 kN to the base shear in the original scenario. For such extensions, one may also revisit the constant load shape assumed within the flow depth and consider a more bottom-heavy distribution, as discussed in Sect. 3.2. Since this study did not address effects of flow fluidization, whether the pressure height concept carries over to the impact of mixed powder snow avalanches remains to be resolved.

- 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*, pp. 1041–1049, <https://doi.org/10.4408/IJEGE.2011-03.B-113>, 2011.
- Austrian Standards International: ÖNORM B 4801, 2024.
- Bartelt, P., Salm, B., and Gruber, U.: Calculating Dense-Snow Avalanche Runout Using a Voellmy-fluid Model with Active/Passive Longitudinal Straining, *Journal of Glaciology*, 45, 242–254, <https://doi.org/10.3189/S002214300000174X>, 1999.
- Bartelt, P., Caviezel, A., Degonda, S., and Buser, O.: Avalanche Impact Pressures on Structures with Upstream Pile-Up/Accumulation Zones of Compacted Snow, *Natural Hazards and Earth System Sciences Discussions*, pp. 1–16, <https://doi.org/10.5194/nhess-2018-154>, 2018.
- Blatny, L., Löwe, H., Wang, S., and Gaume, J.: Computational Micromechanics of Porous Brittle Solids, *Computers and Geotechnics*, 140, 104284, <https://doi.org/10.1016/j.compgeo.2021.104284>, 2021.
- Choi, C. E., Au-Yeung, S. C. H., Ng, C. W. W., and Song, D.: Flume Investigation of Landslide Granular Debris and Water Runup Mechanisms, *Géotechnique Letters*, 5, 28–32, <https://doi.org/10.1680/geolett.14.00080>, 2015.
- Eidevåg, T., Thomson, E. S., Kallin, D., Casselgren, J., and Rasmuson, A.: Angle of Repose of Snow: An Experimental Study on Cohesive Properties, *Cold Regions Science and Technology*, 194, 103470, <https://doi.org/10.1016/j.coldregions.2021.103470>, 2022.
- Faug, T.: Macroscopic Force Experienced by Extended Objects in Granular Flows over a Very Broad Froude-number Range, *The European Physical Journal E*, 38, 34, <https://doi.org/10.1140/epje/i2015-15034-3>, 2015.
- Faug, T.: Impact Force of Granular Flows on Walls Normal to the Bottom: Slow versus Fast Impact Dynamics, *Canadian Geotechnical Journal*, 58, 114–124, <https://doi.org/10.1139/cgj-2019-0399>, 2021.
- Faug, T., Chanut, B., Beguin, R., Naaim, M., Thibert, E., and Baroudi, D.: A Simple Analytical Model for Pressure on Obstacles Induced by Snow Avalanches, *Annals of Glaciology*, 51, 1–8, <https://doi.org/10.3189/172756410791386481>, 2010.
- Gaume, J., Gast, T., Teran, J., van Herwijnen, A., and Jiang, C.: Dynamic Anticrack Propagation in Snow, *Nature Communications*, 9, 3047, <https://doi.org/10.1038/s41467-018-05181-w>, 2018.
- Gravish, N., Umbanhowar, P. B., and Goldman, D. I.: Force and Flow Transition in Plowed Granular Media, *Physical Review Letters*, 105, 128301, <https://doi.org/10.1103/PhysRevLett.105.128301>, 2010.
- Gray, J. M. N. T., Tai, Y.-C., and Noelle, S.: Shock Waves, Dead Zones and Particle-Free Regions in Rapid Granular Free-Surface Flows, *Journal of Fluid Mechanics*, 491, 161–181, <https://doi.org/10.1017/S0022112003005317>, 2003.
- Gubler, H., Hiller, M., Klaussegger, G., and Suter, U.: Messungen an Fliesslawinen. Zwischenbericht 1986, Tech. Rep. 41, Eidg. Institut f. Schnee- und Lawinenforschung, CH-7260 Weissfluhjoch/Davos, 1986.
- Hákonardóttir, K. M.: A Laboratory Study of the Interaction between Supercritical, Shallow Flows and Dams, no. 03038 in *Greinargerð / Veðurstofa Íslands*, Veðurstofa Íslands, Reykjavík, 2003.
- Hauksson, S., Pagliardi, M., Barbolini, M., and Jóhannesson, T.: Laboratory Measurements of Impact Forces of Supercritical Granular Flow against Mast-like Obstacles, *Cold Regions Science and Technology*, 49, 54–63, <https://doi.org/10.1016/j.coldregions.2007.01.007>, 2007.
- Huber, A., Gems, B., Oesterle, F., and Granig, M.: 3D-numerische Modellierung Der An- Und Umströmung von Seilbahnmasten Durch Fließprozesse Mit Flow-3D, *WLV Journal*, 85, 271–272, <https://www.wlv-austria.at/journal/journal-archiv/56-2021-heft-187>, 2021.
- Iverson, R. M., George, D. L., and Logan, M.: Debris Flow Runup on Vertical Barriers and Adverse Slopes, *Journal of Geophysical Research: Earth Surface*, 121, 2333–2357, <https://doi.org/10.1002/2016JF003933>, 2016.

- Jóhannesson, T., Gauer, P., Issler, D., and Lied, K., eds.: *The Design of Avalanche Protection Dams - Recent Practical and Theoretical Developments*, Publications Office of the European Union, Brussels, <https://doi.org/doi/10.2777/12871>, 2009.
- Kamrin, K., Hill, K. M., Goldman, D. I., and Andrade, J. E.: *Advances in Modeling Dense Granular Media*, *Annual Review of Fluid Mechanics*, 56, 215–240, <https://doi.org/10.1146/annurev-fluid-121021-022045>, 2024.
- 545 Köhler, A., McElwaine, J. N., and Sovilla, B.: *GEODAR Data and the Flow Regimes of Snow Avalanches*, *Journal of Geophysical Research: Earth Surface*, 123, 1272–1294, <https://doi.org/10.1002/2017JF004375>, 2018.
- 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>, 2026a.
- Kohler, M. J., Gaume, J., Ancey, C., and Sovilla, B.: *Dataset Accompanying the Research Article "Distinguishing Run-up Height from Pressure Distribution during Avalanche Impact on Narrow Obstacles: Mechanisms and Semi-Empirical Prediction from Three-Dimensional Simulations"*, <https://doi.org/10.5281/zenodo.18847594>, 2026b.
- 550 Kyburz, M. L., Sovilla, B., Gaume, J., and Ancey, C.: *Decoupling the Role of Inertia, Friction, and Cohesion in Dense Granular Avalanche Pressure Build-up on Obstacles*, *Journal of Geophysical Research: Earth Surface*, 125, e2019JF005 192, <https://doi.org/10.1029/2019JF005192>, 2020.
- 555 Kyburz, M. L., Sovilla, B., Gaume, J., and Ancey, C.: *Physics-Based Estimates of Drag Coefficients for the Impact Pressure Calculation of Dense Snow Avalanches*, *Engineering Structures*, 254, 113 478, <https://doi.org/10.1016/j.engstruct.2021.113478>, 2022.
- Kyburz, M. L., Sovilla, B., Bühler, Y., and Gaume, J.: *Potential and Challenges of Depth-Resolved Three-Dimensional MPM Simulations: A Case Study of the 2019 ‘Salezer’ Snow Avalanche in Davos*, *Annals of Glaciology*, pp. 1–14, <https://doi.org/10.1017/aog.2024.14>, 2024.
- Li, X., Sovilla, B., Jiang, C., and Gaume, J.: *The Mechanical Origin of Snow Avalanche Dynamics and Flow Regime Transitions*, *The Cryosphere*, 14, 3381–3398, <https://doi.org/10.5194/tc-14-3381-2020>, 2020.
- 560 Li, X., Sovilla, B., Jiang, C., and Gaume, J.: *Three-Dimensional and Real-Scale Modeling of Flow Regimes in Dense Snow Avalanches*, *Landslides*, 18, <https://doi.org/10.1007/s10346-021-01692-8>, 2021.
- Li, X., Sovilla, B., Gray, J. M. N. T., and Gaume, J.: *Transient Wave Activity in Snow Avalanches Is Controlled by Entrainment and Topography*, *Communications Earth & Environment*, 5, 1–11, <https://doi.org/10.1038/s43247-023-01157-x>, 2024.
- 565 Lin, B., Wu, Y., Niu, Z., and Wang, D.: *Flow Jump Regimes of Inclined Granular Flow Interacting with Downstream Wall-like Obstacle*, *Powder Technology*, 465, 121 342, <https://doi.org/10.1016/j.powtec.2025.121342>, 2025.
- Margreth, S., Stoffel, L., and Schaer, M.: *Berücksichtigung der Lawinen- und Schneedruckgefährdung bei Seilbahnen. Ein Leitfaden für die Praxis*, WSL Berichte, 2015.
- McClung, D. M. and Mears, A. I.: *Dry-Flowing Avalanche Run-up and Run-Out*, *Journal of Glaciology*, 41, 359–372, <https://doi.org/10.3189/S0022143000016233>, 1995.
- 570 Mejean, S., Faug, T., and Einav, I.: *A General Relation for Standing Normal Jumps in Both Hydraulic and Dry Granular Flows*, *Journal of Fluid Mechanics*, 816, 331–351, <https://doi.org/10.1017/jfm.2017.82>, 2017.
- Metcalf, J. R.: *Angle of Repose and Internal Friction*, *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, 3, 155–161, [https://doi.org/10.1016/0148-9062\(66\)90005-2](https://doi.org/10.1016/0148-9062(66)90005-2), 1966.
- 575 Ortiz, M. and Pandolfi, A.: *A Variational Cam-clay Theory of Plasticity*, *Computer Methods in Applied Mechanics and Engineering*, 193, 2645–2666, <https://doi.org/10.1016/j.cma.2003.08.008>, 2004.
- Ortner, G., Bründl, M., Kropf, C. M., Rössli, T., Bühler, Y., and Bresch, D. N.: *Large-Scale Risk Assessment on Snow Avalanche Hazard in Alpine Regions*, *Natural Hazards and Earth System Sciences*, 23, 2089–2110, <https://doi.org/10.5194/nhess-23-2089-2023>, 2023.

Ritter, J., Löwe, H., and Gaume, J.: Microstructural Controls of Anticrack Nucleation in Highly Porous Brittle Solids, *Scientific Reports*, 10, 12 383, <https://doi.org/10.1038/s41598-020-67926-2>, 2020.

Roscoe, K. H. and Burland, J. B.: On the Generalised Stress-Strain Behaviour of ‘Wet’ Clay, *Engineering Plasticity*, pp. 535–609, 1968.

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.

Salm, B., Burkard, A., and Gubler, H. U.: Berechnung von Fliesslawinen. Eine Anleitung für Praktiker mit Beispielen, Tech. Rep. 47, Eidgenössisches Institut für Schnee- und Lawinenforschung, Weissfluhjoch/Davos, 1990.

Savage, S. B. and Hutter, K.: The Motion of a Finite Mass of Granular Material down a Rough Incline, *Journal of Fluid Mechanics*, 199, 177–215, <https://doi.org/10.1017/S0022112089000340>, 1989.

Simo, J. C. and Meschke, G.: A New Class of Algorithms for Classical Plasticity Extended to Finite Strains. Application to Geomaterials, *Computational Mechanics*, 11, 253–278, <https://doi.org/10.1007/BF00371865>, 1993.

Sovilla, B., Schaer, M., Kern, M., and Bartelt, P.: Impact Pressures and Flow Regimes in Dense Snow Avalanches Observed at the Vallée de La Sionne Test Site, *Journal of Geophysical Research: Earth Surface*, 113, <https://doi.org/10.1029/2006JF000688>, 2008a.

Sovilla, B., Schaer, M., and Rammer, L.: Measurements and Analysis of Full-Scale Avalanche Impact Pressure at the Vallée de La Sionne Test Site, *Cold Regions Science and Technology*, 51, 122–137, <https://doi.org/10.1016/j.coldregions.2007.05.006>, 2008b.

Stomakhin, A., Schroeder, C., Chai, L., Teran, J., and Selle, A.: A Material Point Method for Snow Simulation, *ACM Transactions on Graphics*, 32, 102:1–102:10, <https://doi.org/10.1145/2461912.2461948>, 2013.

Sulsky, D., Chen, Z., and Schreyer, H. L.: A Particle Method for History-Dependent Materials, *Computer Methods in Applied Mechanics and Engineering*, 118, 179–196, [https://doi.org/10.1016/0045-7825\(94\)90112-0](https://doi.org/10.1016/0045-7825(94)90112-0), 1994.

Techel, F., Jarry, F., Kronthaler, G., Mitterer, S., Nairz, P., Pavšek, M., Valt, M., and Darms, G.: Avalanche Fatalities in the European Alps: Long-Term Trends and Statistics, *Geographica Helvetica*, 71, 147–159, <https://doi.org/10.5194/gh-71-147-2016>, 2016.

Thibert, E., Baroudi, D., Limam, A., and Berthet-Rambaud, P.: Avalanche Impact Pressure on an Instrumented Structure, *Cold Regions Science and Technology*, 54, 206–215, <https://doi.org/10.1016/j.coldregions.2008.01.005>, 2008.

Tregaskis, C., Johnson, C. G., Cui, X., and Gray, J. M. N. T.: Subcritical and Supercritical Granular Flow around an Obstacle on a Rough Inclined Plane, *Journal of Fluid Mechanics*, 933, A25, <https://doi.org/10.1017/jfm.2021.1074>, 2022.

Vallero, G., Marchelli, M., and De Biagi, V.: Structural Vulnerability of Power Transmission Line Supports: Development of Fragility Curves for Snow Avalanche Loads, *Georisk: Assessment and Management of Risk for Engineered Systems and Geohazards*, 0, 1–23, <https://doi.org/10.1080/17499518.2026.2616777>, 2026.

Védrine, L., Li, X., and Gaume, J.: Detrainment and Braking of Snow Avalanches Interacting with Forests, *Natural Hazards and Earth System Sciences*, 22, 1015–1028, <https://doi.org/10.5194/nhess-22-1015-2022>, 2022.

Virtanen, P., Gommers, R., Oliphant, T. E., Haberland, M., Reddy, T., Cournapeau, D., Burovski, E., Peterson, P., Weckesser, W., Bright, J., van der Walt, S. J., Brett, M., Wilson, J., Millman, K. J., Mayorov, N., Nelson, A. R. J., Jones, E., Kern, R., Larson, E., Carey, C. J., Polat, İ., Feng, Y., Moore, E. W., VanderPlas, J., Laxalde, D., Perktold, J., Cimrman, R., Henriksen, I., Quintero, E. A., Harris, C. R., Archibald, A. M., Ribeiro, A. H., Pedregosa, F., van Mulbregt, P., and SciPy 1.0 Contributors: SciPy 1.0: Fundamental Algorithms for Scientific Computing in Python, *Nature Methods*, 17, 261–272, <https://doi.org/10.1038/s41592-019-0686-2>, 2020.

Voellmy, A.: Über die Zerstörungskraft von Lawinen; Zur Dynamik der Lawinen, *Schweizerische Bauzeitung*, 73, <https://doi.org/10.5169/SEALS-61891>, 1955.

- Willibald, C., Löwe, H., Theile, T., Dual, J., and Schneebeli, M.: Angle of Repose Experiments with Snow: Role of Grain Shape and Cohesion, *Journal of Glaciology*, 66, 658–666, <https://doi.org/10.1017/jog.2020.36>, 2020.
- Wu, Y., Wang, D., Li, P., and Niu, Z.: Experimental Investigation of Dry Granular Flows down an Inclined Channel against a Wall-like Obstacle of Limited Width, *Acta Geotechnica*, 18, 2141–2154, <https://doi.org/10.1007/s11440-022-01714-2>, 2023.