

WHAT ARE THE LIMITATIONS OF DYNAMICAL MODEL USE IN AVALANCHE CONSULTANCY TODAY?

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ABSTRACT: Understanding the limitations of dynamical modelling approaches is essential to providing accurate and useful information to clients. In avalanche consultancy, one may find themselves addressing many avalanche problems at short notice, for example, assessing the impact of many avalanche paths along critical infrastructure. Fast-running dynamical models, such as the depth-averaged Voellmy friction-law type, serve as indispensable tools in this context, swiftly providing insights into avalanche properties like runout distances. While these models perform well in predicting runout, their optimisation for speed and scale may lead to the neglect of other crucial properties. For instance, they are implicitly restricted to dry dense configurations, with constant density assumptions neglecting powder or fluidised effects. Additionally, their empirical parameterisation on limited runout data raises concerns about their applicability across diverse climate and topographic regions. Moreover, their reliance on initial avalanche volume may not accurately capture the physical properties of real avalanches, introducing uncertainties. For certain consultancy applications, some models may outperform others. Improved practices are essential for generating more accurate runout maps, determining pressure criteria, estimating avalanche flow times, dimensioning mitigation measures, and assessing climate change impacts. A possible solution lies in leveraging adaptable frameworks that offer consultants a range of modelling options tailored to specific applications. For instance, if avalanche speed is crucial, more sophisticated depth-averaged approaches may be preferable. For scenarios involving transitions from wet snow avalanches to slush flows, multi-layer or multi-phase models may offer better insights. Likewise, for dimensioning purposes, models like Material Point Method (MPM) or 3D continuum methods could prove more effective, accounting for depth variations. This paper will discuss the importance of understanding and addressing the limitations of dynamical avalanche models in consultancy. By adopting versatile modelling frameworks, consultants can tailor their approaches to diverse applications, thereby improving the accuracy and reliability of their assessments for clients.

Keywords: Snow avalanche dynamics, numerical modelling, depth-averaged modelling.

1. INTRODUCTION

To tailor the direction of research objectives within the “Applied Avalanche Research in Norway (AARN)” project, conducted at the Norwegian Geotechnical Institute (NGI), we performed a critical study to examine the current state of dynamical avalanche modelling used widely within avalanche consultancy. Our objective with this paper is to stimulate discussion about the development of more adaptable modelling frameworks that deliver enhanced accuracy and reliability for con-

sultancy tasks. With a change in the needs of consultants from targeting good and reliable hazard maps to more complex tasks, such as, determining pressure criteria, estimating avalanche flow times, dimensioning mitigation measures, and assessing climate change impact, changes must also come to the modelling tools designed to assist consultants. The prevalent numerical methods, such as RAMMS, DAN3D, SAMOS AT and others, were designed with optimisations towards runout modelling and provide valuable information for consultants within that context (Savage and Hutter, 1989; Christen et al., 2010; Sampl and Zwinger, 2004; McDougall and Hungr, 2004). However, these models often rely on oversimplified assumptions that inadequately capture the velocity-dependent properties of avalanches, such as impact pressures. Given Norway’s complex terrain, changing climate and level of avalanche vulnerability, it is essential

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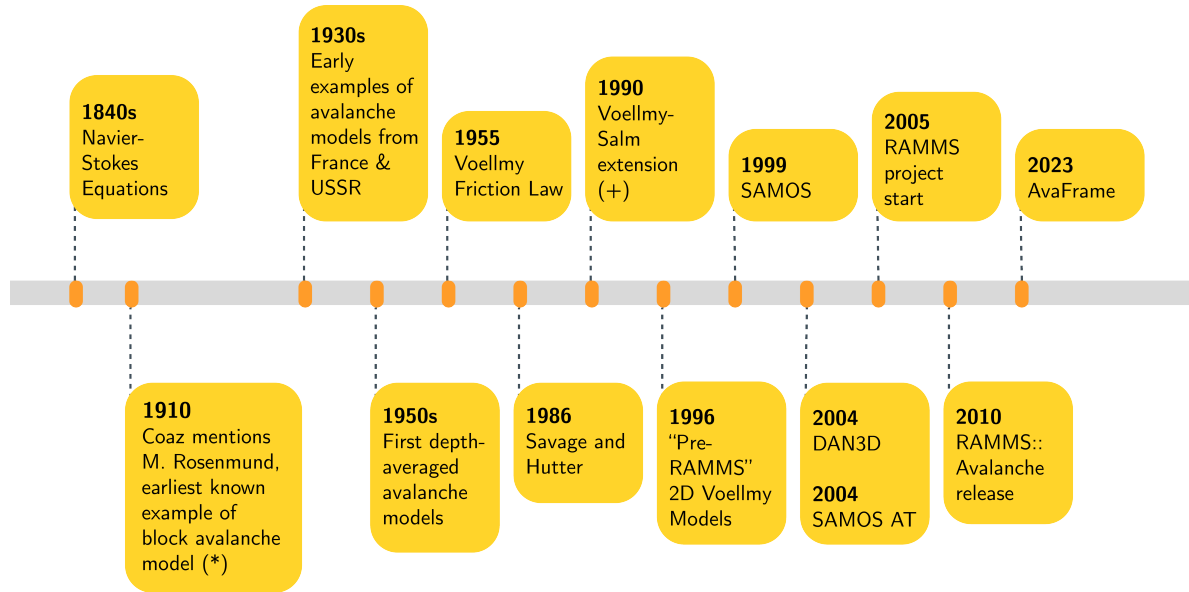


Fig. 1: Timeline showing a selection of key events in the development of Voellmy-type depth-averaged dynamical snow avalanche models. (*) Coaz (1910); Schenk (2017), (+) Salm (2004).

that we keep advancing these models to support the nation's avalanche prediction and mitigation strategies. To do this, we must bring the most up-to-date and appropriate models to a point where they are accessible for consultants and continue to develop models that improve the outlook of various consultancy tasks.

The foundational Voellmy friction model, introduced in 1955 (Voellmy, 1955, 1964), has been the cornerstone of numerical tools widely used in consultancy since the mid-2000s, see figure 1. However, the field of avalanche modelling has undergone substantial evolution since then, including advancements in mathematical modelling, computational capabilities, data integration, and a deeper understanding of avalanche mechanics. To optimise the safety and reliability of avalanche risk assessments in Norway, we advocate for a re-evaluation and modernisation of our methodologies.

This paper underscores the importance of recognising and addressing the limitations inherent in the depth-averaged Voellmy friction models widely used within the consultancy sector. We suggest that by embracing more versatile modelling frameworks, consultants can tailor their approaches to a wider range of applications, ultimately improving the precision and dependability of their assessments. Our analysis is grounded in a comprehensive, albeit non-exhaustive, review of the current landscape of dynamical avalanche modelling in both research

and consultancy. The literature review included contributions from a wide range of sources including snow avalanches, granular mechanics, mathematical and numerical modelling and the modelling of other relevant geophysical mass flows, such as landslides, debris flows, lahars and pyroclastic flows (Tregaskis and Gauer, 2024).

The subsequent sections discuss the utilisation of dynamical models in contemporary consultancy, examining the strengths and weaknesses of the prevailing Voellmy friction-based models. We also consider the directions which current research can assist in, given our overview of cutting-edge research in granular flow mechanics and avalanche phenomenology. Finally, we discuss recommendations for advancing avalanche consultancy through further research, adaptation of new models for practical use, and the refinement of consultancy practices.

2. PROBLEM ENVIRONMENT

Consultancy work requires models capable of simulating avalanche behaviour on a scale relevant to real-world scenarios. While large-scale assessments, covering potentially thousands of avalanche paths, prioritise computational efficiency, (see e.g., ISSLER et al., 2023; ORTNER et al., 2022), smaller-scale projects, such as planning mitigation measures, de-

mand greater accuracy. The choice of model often hinges on a trade-off between speed and precision.

Assessing the risk posed by natural hazards in mountainous regions involves evaluating historical event frequency, potential future occurrences, and potential impacts on people and infrastructure. While expert judgment and historical data provide valuable insights, quantifying these factors with precision remains challenging due to the rarity of such events and the influence of climate change (Eckert et al., 2009). A central application is to estimate the runout length of prototypical large avalanches. Historically two approaches have been utilised; statistical models (see *e.g.*, Lied and Bakkehøi, 1980), and dynamical models (see figure 1). For impact assessments of this type, dynamical mathematical models offer a critical tool by simulating avalanche behaviour to predict flow paths, deposits, and potential impacts. When combined, these methods help practitioners to delineate areas with a high level of hazard and conduct risk assessments (NVE, 2020).

The integration of these models into modern avalanche consultancy is a critical area of focus. As external conditions evolve, it is essential to determine how new and existing research in dynamical modelling can enhance the capabilities of practitioners. A key question is whether current models and practices are sufficiently robust to address the uncertainties inherent in avalanche assessment. For example, establishing appropriate intensity criteria for avalanche events involves understanding factors contributing to the pressure distribution of an avalanche, such as volume, speed and density. This is especially pertinent given the effect of climate change on assessing avalanche hazard. This involves analysing potential shifts in weather effects, snowpack conditions and avalanche frequency (perhaps more wet snow avalanches in a typical winter season). Adapting existing models or developing new ones to account for differing avalanche types is crucial for proactive risk management.

There is also a need for improved warning systems for closure of exposed transport infrastructure. The development of models that can reliably predict avalanche paths and impact timings given a detected avalanche release could be crucial for projects of this nature. These tasks necessitate models capable of predicting the avalanche path, extent, and timing with precision.

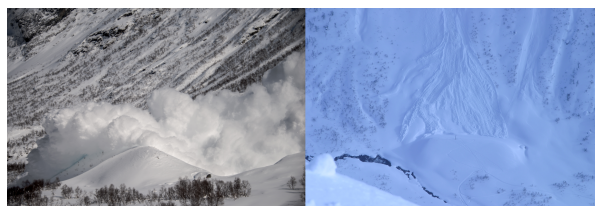


Fig. 2: Photographs depicting some of the complex phenomenology present in snow avalanches at the Ryggfonn test site in Norway. Left shows the interaction of a fast, dry snow avalanche with a catchment dam. Right shows the still moving dense flow that has fingered at the front leaving levees in the deposit. This highlights the different flow regimes present in an avalanche.

Furthermore, depending on the scale and accuracy required of the task, to accurately represent complex avalanche phenomena, models must incorporate erosion, entrainment, deposition, obstacle interactions (both natural, like forests or terrain features, and man-made, like dams or fences), wave formation, and three-dimensional flow dynamics, including multi-phase considerations, see figure 2.

As the research stands today, the most sophisticated models have made improvements in all of these areas, thus, utilisation of advanced dynamical modelling offers substantial potential for advancing avalanche consultancy. However, the complexity of real-world avalanches remains a significant challenge. Consultants must carefully evaluate the relevance of these complexities when assessing specific scenarios. While increasing model sophistication can improve results, it also demands additional resources, and therefore, additional cost and expertise. Striking an optimal balance between model complexity and practical application is crucial. In the realm of natural hazard assessment, where human lives and livelihoods are at stake, the justification for such increased complexity might often be justified.

Dynamical models are designed to simulate different stages of an avalanche, from release to deposition. However, they inherit uncertainties from preceding stages, such as the weather and snow conditions prior to the avalanche release. For instance, errors in estimated release volume and area can influence the avalanche's interaction with the terrain and ultimately its flow behaviour and runout. To address this in consultancy applications, many approaches incorporate probabilistic estimates and expert judgment for avalanche release characteristics. While effective in many cases, this highlights a limitation of current models, the lack of prior in-

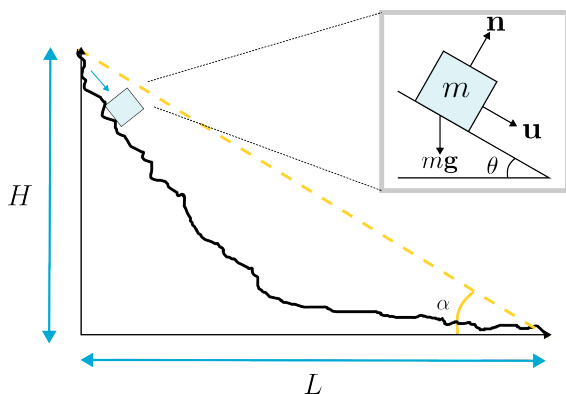


Fig. 3: Idealisation of an avalanche on a mountainside given by a schematic diagram of a block on a path. Zooming in on our block allows us to isolate a free body diagram of the forces acting on the block.

formation necessitates that models provide insights into idealised flows rather than the full complexity of real-world avalanches.

3. PROS AND CONS OF THE DEPTH-AVERAGED VOELLMY FRICTION MODEL FOR SNOW AVALANCHES

This section breaks down the depth-averaged Voellmy friction avalanche model into what works well, and is desirable in future models, and what should be improved or is a crucial limitation of the approach. Assessing such models requires distinguishing between the numerical implementation and the underlying mathematical model. Commercial software often uses private thresholding and limiting techniques, complicating assessments of the numerical methods utilised. Due to this, we focus on the strengths and weaknesses of the underlying model and determine its suitability for specific use cases.

Depth-averaged models offer computational efficiency crucial for large-scale avalanche simulations but simplify the complex three-dimensional flow dynamics. While capturing essential physical processes, these models inherently lose information about vertical variations, for example, they cannot represent phenomena like vortices or depth-dependent density changes. Additionally, depth-averaging introduces challenges in modelling curvature effects, erosion, and entrainment, despite efforts to incorporate these processes. The key lies in balancing the need for computational efficiency with the desire for physical realism to enhance model performance.

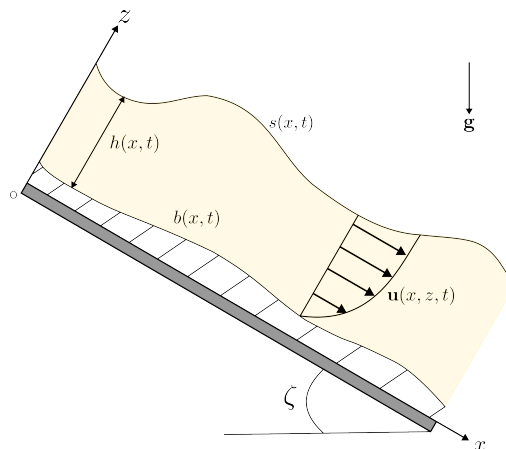


Fig. 4: Schematic diagram of a granular avalanche. The coordinate system is defined on the plane, inclined to an angle ζ , with x pointing downslope and z in the outward normal direction. The functions $b(x, t)$ and $s(x, t)$ define the basal topography and surface of the flow respectively and, thus, define the flow thickness $h(x, t) = s(x, t) - b(x, t)$. The vertical velocity profile $\mathbf{u}(x, z, t)$ is assumed in advance. Using this setup the depth-averaged equations can describe an avalanche flow without explicitly needing to solve for the vertical direction.

The depth-averaged models utilise the assumption that avalanches are far longer and wider than they are thick to promote the idea that simplifying the equations over the depth will maintain the most important properties of the flow. This simplification works surprisingly well in a lot of cases for fluid flows and is widely applied across the sciences. A schematic diagram showing the setup of a depth-averaged model for a granular flow is shown in figure 4.

A simple block model version of the momentum equation highlights where the parameterisation dictating avalanche dynamics in the Voellmy friction law comes into play, see figure 3,

$$\underbrace{\frac{dU}{dt}}_{\text{acceleration}} = \underbrace{g \sin \theta}_{\text{driving}} - \underbrace{a_0 g \cos \theta}_{\text{Coulomb friction}} - \underbrace{a_2 U^2}_{\text{velocity dependent friction}} \quad (1)$$

Here U is the velocity, t time, g acceleration due to gravity and θ local slope angle. The parameters $a_0 = \mu$ and $a_2 = g/(\xi h)$ control the retarding force through a constant Coulomb friction term and a velocity dependent turbulent friction term. Other mathematical models specialising in different materials' properties take a similar form to this, with a_0

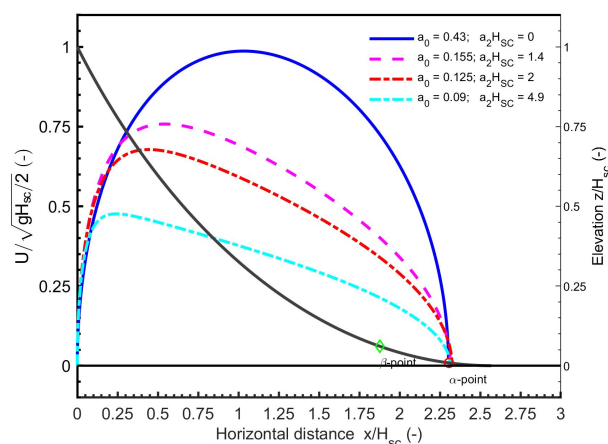


Fig. 5: Comparison of non-dimensionalised speed profiles for a range of Voellmy parameterisations on a parabolic track (black line). The figure shows how for the same runout length (at the α -point) one can get vastly different physical behaviours using only slightly varied Voellmy parameters. (Adapted from Gauer et al., 2023)

and a_2 taking different values (note this model is independent of mass).

It is a common misconception that the use of these models provides completely accurate and physical results, when, in fact, they are heavily reliant on approximations. They explicitly rely on empirical relations that are not strictly connected to the material's rheology (physical description of how the material flows). For example, the Voellmy turbulent term ξ in the widely-applied friction law does not come out from the constitutive laws governing fluid flow in the momentum formulation but is instead empirically defined (Voellmy, 1955). In practice this means that the numerical value given for ξ parameter propagates through the model and does not affect the momentum through physically defined mechanisms which ultimately leads to errors in the frictional description.

These approximations made to the full mathematical description are necessary because of how difficult it is to solve the non-linearity of the complex processes in an avalanche flow. For example, a dense, thick slow-moving avalanche may run out to the same distance as a dilute, fast, but shallow, avalanche. Thus, applying mathematical models to the complex terrain of a mountainside requires numerical solutions, as analytical solutions (complete solutions to the equations) are often not possible.

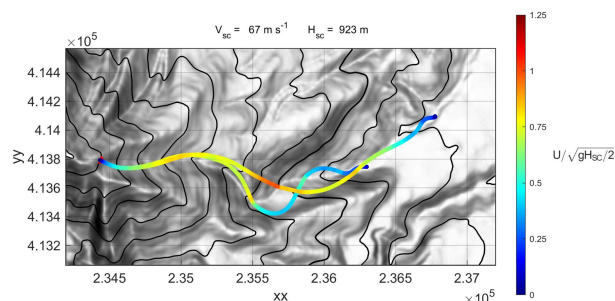


Fig. 6: Simulation of a 2D mass block model with variable mass, based on Gauer (2020), for the Makunosawa avalanche in Japan. The two paths shown vary significantly and have very different runout lengths, but, only have a slight difference in frictional parameters. This highlights the importance of capturing good velocity estimates for predicting avalanche paths and runouts.

The limitations of the Voellmy parameterisation are highlighted in figures 5–7. Figure 5 shows how for the same runout length a large variety of downslope velocity profiles can be expected. This corresponds to differences in the material properties and is the reason for the existence of the parameterisation tables for a variety of choices when using a model like RAMMS in practice. Note, this enters a subjective choice in the model at the discretion of the consultant. However, these choices can have large effects on the avalanche properties. For example, in figure 6, we see that small changes in the parameters can cause very different avalanche paths that traverse the terrain in different ways, highlighting the need for accurate velocity prediction for complex avalanche paths. This is also highlighted in figure 7, where we compare an artificially released avalanche in 2021 at the Ryggfonn test-site to a RAMMS simulation with default parameterisation. At 50 seconds into the flow from release, the avalanches display wildly different properties with the simulation halfway down the path when the real avalanche had hit the dam. This highlights how careful consultants need to be when applying these equations for velocity dependent tasks as small errors can lead to big changes in behaviour.

The current parameterisation of the Voellmy friction law in avalanche modelling has fundamental flaws. Due to volume dependency, it inadequately accounts for the differing behaviours between wide, shallow avalanches and tall, thick ones of the same volume, leading to inaccuracies. Additionally, the model fails to capture the effects of

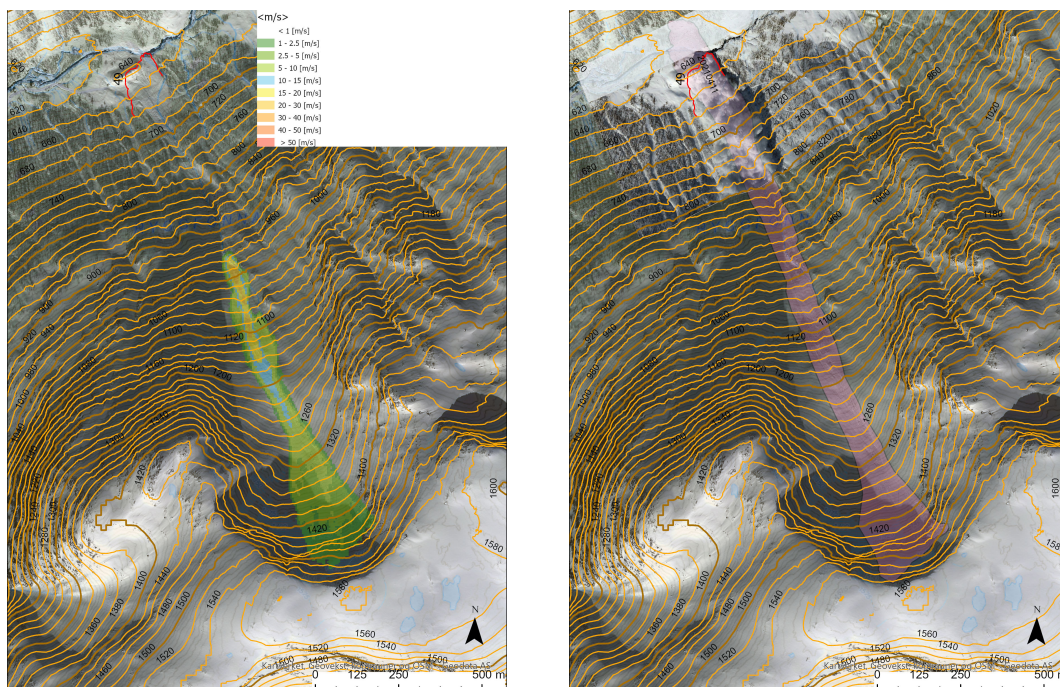


Fig. 7: Shows a comparison between speed profiles of RAMMS using a default parameterisation and a real-world Ryggfonn avalanche (11.04.2021) at 50s into the flow from release. We see a huge difference in the avalanche behaviour.

granular hysteresis and the physics of deposition processes. The limited data available often biases the model toward predicting runout distances, which can compromise the accuracy of velocity predictions. This results in significant uncertainties in predicting avalanche paths and timings, as models that effectively capture runout distances can and do yield poor velocity predictions.

Hazard assessments are further complicated by erratic weather patterns, such as rain-on-snow events, increasing the frequency and variety of avalanches. The influence of climate change necessitates a more robust approach to avalanche prediction, incorporating extreme value statistics and a better understanding of changing mechanics. This is particularly relevant for wet, dense avalanches or slush flows, which require different parameterisations due to the interactions between fluid and snow/ice aggregates. Moreover, the differing material behaviour must address the climatic and topographic differences, as regional climate nuances, such as coastal weather systems, can significantly impact avalanche dynamics. This suggests that geographic location and the uncertainties in historical avalanche data will influence the reliability of current parameterisation methodologies. A

shift towards friction laws based on material properties of snow may offer a more consistent and future-proof approach to avalanche modelling, accommodating the increasing variability introduced by climate change.

Computational efficiency is crucial in consultancy, a model that takes weeks to run on a supercomputer is both costly and impractical compared to one that delivers results in minutes on a laptop. Highly detailed simulations may not be necessary, especially given the uncertainties in initial conditions and snowpack properties. In many cases, simpler models may be more suitable due to their generality and applicability across diverse scenarios. Understanding the required level of accuracy, whether a full velocity field or a bulk velocity estimation, is necessary for the effective use of these models. Methods such as RAMMS or DAN3D are user-friendly, integrating well with GIS software, and their widespread use provides consistency and comparability across studies. When evaluating model performance, key considerations include the speed of obtaining results, ease of interpretation, and the accuracy of predictions.

4. OVERVIEW OF EXISTING RESEARCH MODELS

Avalanche research encompasses a broad spectrum of studies investigating various aspects of avalanche behaviour and modelling techniques. A comprehensive literature review was conducted to identify recent and significant advancements in avalanche modelling (Tregaskis and Gauer, 2024). Many cutting-edge models leverage sophisticated mathematical and computational methods, coupled with a deeper understanding of nonlinear fluid dynamics and high-performance computing, to simulate and predict diverse aspects of avalanche behaviour.

These most up-to-date models focus on various aspects of avalanche behaviour, currently not captured by the most commonly used consultancy models. For example, more advanced depth-averaged models are capable of capturing more complex topographical effects, including the simulation of phenomena like jets and shocks that significantly influence avalanche paths and energy dissipation, (see *e.g.*, Viroulet et al., 2017; Tregaskis et al., 2022). These models can also simulate a wide range of physical features, such as surges, self-channelisation, and interactions with forests (Edwards et al., 2017; Rocha et al., 2019). Furthermore, advancements in computing power enable higher resolution simulations and more advanced methods, providing more detailed insights into avalanche evolution (see *e.g.*, Kyburz et al., 2023).

The flexibility of these models is another key advantage, as they can be applied to various scales, from individual avalanche paths to regional assessments. Rigorous verification and validation against real-world avalanche events enhances the reliability and accuracy of these models. By employing these advanced models, researchers and practitioners can achieve improved prediction accuracy, a deeper understanding of avalanche dynamics, and more effective risk assessment and mitigation strategies.

To bridge the gap between research and consultancy, further efforts are needed to adapt these models for practical applications. Often research models are left obfuscated and unusable by consultants. While the literature review offered a comprehensive overview of research endeavours in avalanche dynamics modelling, highlighting potential applications in consultancy, it is important to note that this was non-exhaustive and serves as a

starting point for exploring the latest advancements in the field.

5. DISCUSSION AND CONCLUSIONS

It is crucial to explore recent and quickly developing research in avalanche modelling, understand its improvements and objectives, and evaluate its accessibility for consultancy use. Identifying community needs involves understanding current practices and problems. With use cases like intensity criteria, diverse avalanche types and real-time hazard warnings on the horizon for dynamic models, we need to assess current model limitations and identify what improvements new models should attain to best assist in hazard assessment. The discussion extends to the comparison between research codes and commercial codes, with a critical examination needed of whether they provide sufficient information for certain tasks or if there is a necessity to establish practices utilising more sophisticated and targeted models.

This paper outlines key uses of dynamical models in consultancy practices and identifies where the weak points of current methodologies are. We establish that the Voellmy friction law depth-averaged models work well for tasks that cover expansive areas and for tasks that facilitate statistical/probabilistic methods. However, these models do not perform as well for tasks requiring higher levels of accuracy or provide information about the timings or velocities of the avalanche flow. In addition, we note that these weaknesses may compound into less certain hazard maps as properties like avalanche paths might be misrepresented, particularly for rare, far-running avalanches that are the focus in many cases.

It is often suggested that a solution to these problems is to provide specialised parameterisation tables for different areas, for example, one for Switzerland and one for Norway. However, caution is advised, considering the evident pitfalls in the validation of the tables, particularly concerning volume dependency. The underlying problems would still remain, and thus, with such an approach one would only cure the symptoms and not the cause.

Avalanche consultants should adjust model use appropriately to the complex behaviour avalanches may exhibit relevant for their project. Thus, we should promote the use of, and develop to meet the challenge, open-source modelling frameworks,

such as AvaFrame (Tonnel et al., 2023), to provide consultants with greater versatility in model choice.

It is crucial that researchers bridge the gap between research models and practical applications by providing clear documentation and workflow examples. This can be achieved through handbooks and workshops designed for consultants. Consultants must exercise caution when using Voellmy-type depth-averaged models for velocity-dependent tasks, carefully justifying parameter choices and acknowledging potential errors. We should prioritise the development and utilisation of models that excel in predicting avalanche velocities and pressure criteria, recognising the importance of addressing multi-phase flows. Focusing funding proposals on these challenges is essential for advancing the use of dynamical models in avalanche consultancy.

To advance the field of avalanche consultancy and mitigate risks effectively, a collaborative effort involving policymakers, consultants, and modelling experts is imperative. This paper advocates for a diversified modelling approach to address the multifaceted nature of avalanche hazards. By leveraging existing open-source frameworks and fostering a deeper understanding of model strengths and limitations, consultants can enhance the accuracy and reliability of their assessments. Continued research focused on improving model capabilities, particularly in areas such as velocity prediction and complex flow phenomena, is crucial. Ultimately, the goal is to build resilience against the evolving challenges posed by mountain hazards, ensuring the safety and well-being of communities.

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