IMPROVING THE DATA BASIS FOR THE PRACTICAL ASSESSMENT OF SNOW SLIDE IMPACTS FOR PRACTICAL AVALANCHE ENGINEERING AND HAZARD MAPPING APPLICATIONS IN AUSTRIA

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ABSTRACT: Snow slide hazard and risk assessment is increasingly relevant in the operational work of the Austrian Service for Torrent and Avalanche Control (WLV). Estimating potential runout distances and associated impact pressures for these small-scale processes is required in a growing number of applications. While established tools for assessing full-size avalanches exist, these approaches are often not directly applicable or practical for smaller-scale snow slide processes. Motivated by two major snow slide cycles in North and East Tyrol during the winters of 2019/20 and 2020/21, an adapted model for the numerical simulation of snow slides has been developed, implemented in the open-source framework AvaFrame (`https://avaframe.org`), and evaluated in accompanying studies. However, in resource-constrained situations and day-to-day operational settings detailed numerical modeling at the slope scale is not always feasible. In these cases simplified surrogate models or ad-hoc heuristics are desirable to provide rapid preliminary assessments. Realizing this practical demand this study sought to utilize `AvaFrame/com5SnowSlide` to derive simplified rapid assessment tools for snow slides. We analyzed 2D profiles of 150 snow slide slopes and constructed a set of 15 representative idealized snow slide topographies on which we performed `com5SnowSlide` simulations with varying release thickness. The resulting model outputs were analyzed and used to derive reduced-complexity surrogate models for practical hazard assessment. Our results indicate that release thickness and slope inclination are the dominant controls on modeled runout distances and peak impact pressures at the base of slopes prone to snow sliding. Based on these findings we derived two simplified surrogate models for a rapid assessment of the hazard potential in confirmed or suspected snow slide runout areas. Comparison between results of the surrogate models and the actual numerical model for selected case studies shows good agreement. The developed rapid assessment tools enable a quick, conservative, and practical estimation of snow slide impact pressures and runout distances using only a few input parameters. While they do not replace detailed numerical simulations or local expertise, they provide a robust initial assessment for practical applications.

KEYWORDS: Snow slide, avalanche modeling, rapid assessment, surrogate models, avalanche engineering

1. INTRODUCTION

Practical experience from recent years provides evidence that the evaluation of hazards and risk associated with snow slides is becoming increasingly relevant for day-to-day operational work at the Austrian Service for Torrent and Avalanche Control (ger. Wildbach- und Lawinenverbauung, WLV). In this context, assessing potential runouts and associated impact pressures for these processes is required in hazard zone mapping, planning of mitigation measures or the preparation of expert reports for construction projects. While established workflows and tools for assessing full-size avalanches exist, these approaches are not directly applicable or practical for smaller-scale snow slide processes. At the same time, the continued expansion of settlements and infrastructure in Alpine valleys, coupled with changing climatic boundary conditions, is expected to sustain the demand for reliable assessments of snow slide hazards and associated risks.

Motivated by two major glide snow and snow slide cycles in North and East Tyrol during the winters of 2019/20 and 2020/21, a number of steps to improve the methodological basis for this task have already been taken in recent years. In particular, a specifically adapted model for the numerical simulation of snow slides was developed based on the established avalanche simulation software SamosAT. The model has recently been implemented in the open-source framework AvaFrame (`https://avaframe.org`), where it is available as computational module `com5SnowSlide`. Accompanying studies (Tollinger and Granig 2023a; Tollinger and Granig 2023b; Tollinger and Granig 2023c) have since evaluated the model against observed snow slides and expert assessments. They assessed parameter sensitivities and identi-

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fied sensible parameter ranges for practical application. The results showed good agreement between modeled and observed snow slide runouts.

However, detailed numerical modeling at the level of single slopes is not always feasible, for example, in the case of on-site inspections at short notice or under other resource constraints. For these cases simple rapid assessment tools that provide a robust initial assessment are desirable from a practical viewpoint.

Realizing this demand, we utilized `AvaFrame/com5SnowSlide` to derive simple surrogate models for rapid estimation of expected runout lengths and peak pressures at the base of slopes prone to snow sliding. This contribution aims to present the underlying data, the methodology employed, and selected findings to an international audience. Further methodological details and additional results can be found in a project report available in German which will be made available via `https://avaframe.org`.

2. DATA & METHODS

2.1. Snow Slides

We use the term *snow slide* as a translation for the German term *"Schneerutsch"*, which is used in the operational context at WLV. The term describes an intermediary process between *snow gliding* and *small (glide snow) avalanches* and is defined by these (Austria-centric) criteria (Granig et al. 2019; Tollinger and Granig 2023b):

- vertical drop between 30 m and $60 - 80$ m
- practical assessment limited to regions between 500 and 1500 m.a.s.l.
- practical assessment limited to near-planar slopes without significant channeling of the flow.
- no turbulent flow is expected
- snow density assumed with 300 kg m^{-3}
- maximum total snow depth ($\mathrm{SD}^{\mathrm{max}}_{150y}$ [m]) rather than maximum 3-day new snow depth ($\mathrm{3DNSD}^{\mathrm{max}}_{150y}$ [m]) serves as the basis for the evaluation of design events (150-year return period) since the observed gliding plane is often at the ground–snow interface.

These criteria define both the scope of this study and the limits for the intended application of the proposed rapid assessment tools.

2.2. com5SnowSlide

The `AvaFrame` module `com5SnowSlide` implements elastic forces between the numerical particles on top of the particle-grid based dense flow avalanche module `com1DFA` (Tonnel et al. 2023) in order to more realistically capture the behavior of snow slide processes. Compared to larger dry flow avalanches, the snow density for these processes is typically higher, and the velocities and vertical displacements are small enough that cohesive forces within the gliding snow layer cannot be safely neglected any longer (Tollinger and Granig 2023c). For a more detailed description, we refer to the AvaFrame documentation at `https://docs.avaframe.org/en/latest/moduleCom5SnowSlide.html` (Oesterle et al. 2025).

Table 1 lists the configuration for `com5SnowSlide` that was used for the model runs in this study. These settings are based on previous parameter studies (Tollinger and Granig 2023c; Tollinger and Granig 2023a; Tollinger and Granig 2023b). In accordance with Tollinger and Granig (2023b) a DEM resolution of 2 m was used for all numerical simulations performed on idealized and real topographies. All simulations were performed with AvaFrame version 2.0b2 (Oesterle et al. 2025).

2.3. Data

The following data sets were utilized in this study.

A: 150 representative longitudinal profiles of snow slide slopes, where start points represent the top of the (potential) release areas and end points were chosen to include the farthest observed or estimated runouts.

B: 30 reference snow slides with delineated release areas, estimated release thickness, associated hazard zone extent and/or documented runout limits.

Dataset A was used to derive typical topographic characteristics of slopes prone to snow sliding and inform the definition of representative idealized topographies described in 2.4.. Dataset B was used to evaluate results of the numerical model with those of the derived simplified surrogate models (Section. 3.3.).

2.4. Analysis of profiles and definition of idealized topographies

We use the method described by Larsen (2021) and Toft et al. (2023) to automatically analyze the 150 longitudinal profiles. First, we approxi-

Table 1: Used parameter settings for simulations performed with `AvaFrame/com5SnowSlide` as suggested by Tollinger and Granig (2023b).

parameter	value	description
`dt`	0.01	time-step in seconds
`frictModel`	`'Voellmy'`	friction model
`muvoellmy`	0.325	basal friction coefficient μ $[-]$
`xsivoellmy`	$58.$	turbulent friction coefficient ξ [m s^{-2}]
`rho`	$300.$	snow density ρ [kg m^{-3}]
`cohesionMaxStrain`	0.2	Maximum length of numerical particle bonds expressed as the ratio of current to initial bond length $[-]$.
`minDistCohesion`	$1.0\,\mathrm{e}^{-3}$	numerical threshold to avoid zero division
`cohesiveSurfaceTension`	50000	cohesive surface tension used as elasticity modulus [N m^{-2}]

mated each profile by a 7^{th} order polynomial. Then we identified different *transit points (TPs)* and *deposition points (DPs)* along these polynomial fits. In this context TPs are defined as points characterizing the transition between release area and avalanche track, and DPs characterize the transition between avalanche track and deposition or runout zones (Fischer 2024; Adams et al. 2024). We used $TP = \beta_{30^\circ}$ to characterize the transition between release area and track, and different $DPs \in \{\beta_{20^\circ}, \beta_{15^\circ}, \beta_{10^\circ}\}$ for the transition between track and deposition zone.

Based on these points, we derived average inclinations for release area (start of the profile to TP), track (start of the profile to DP) and deposition zone (DP to end of profile) for each profile. Table 2 provides an overview of medians and ranges found for the different profile sections identified.

The analysis also served as the base for the definition of 15 representative idealized topographies, that were subsequently utilized for the numerical modeling of snow slides (see Figure 1). The release area inclinations ($28°, 30°, 35°, 40°, 45°$) and vertical drops ($30\,\mathrm{m}, 60\,\mathrm{m}, 80\,\mathrm{m}$) were selected to capture the typical range of observed profiles, the utilized uniform $7.5°$ inclination of the deposition area was selected to represent a conservative mean estimate. Notably the positive inclination of the deposition area represents a more conservative and data based choice than a completely horizontal deposition area as used in previous studies. All idealized topographies were created using the `generateTopo` functions available in `AvaFrame/in3Utils/`. In particular, topographies of the `hockey stick (HS)` type were utilized. These consist of release and deposition areas with constant, user-specified inclinations, connected by a smooth transition.

Table 2: Medians and ranges for release area, track, and deposition area inclinations found for different β points. N denotes the number of profiles, for which respective β points could be automatically identified.

	min, median, max	N
release area		
β_{30°	$25.9°$, $34.8°$, $41.2°$	150
track		
β_{20°	$23.4°$, $32.6°$, $39.3°$	147
β_{15°	$21.4°$, $31.3°$, $37.2°$	145
β_{10°	$21.9°$, $30.3°$, $36.1°$	134
deposition zone		
β_{20°	$-0.2°$, $8.6°$, $19.3°$	147
β_{15°	$-1.6°$, $6.5°$, $20.2°$	145
β_{10°	$-3.1°$, $4.7°$, $15.3°$	134

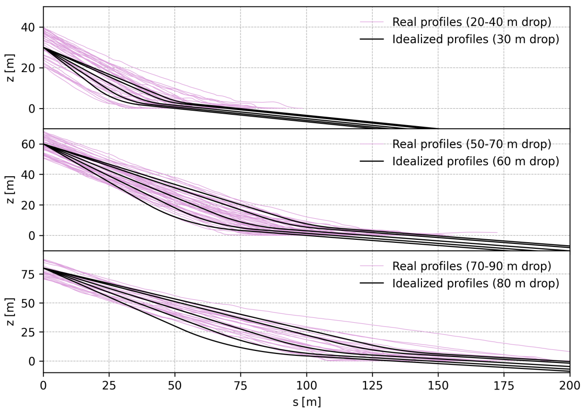


Figure 1: 15 idealized topographies with varying vertical drop $\in \{30\,\mathrm{m}, 60\,\mathrm{m}, 80\,\mathrm{m}\}$ and release area inclination $\in \{28°, 30°, 35°, 40°, 45°\}$ (black solid lines) and selected observed profiles in the same vertical drop range (pink solid lines in the background).

2.5. Parameter variation and analysis of results

For each of the 15 idealized topographies we performed 6 model runs with `com5SnowSlide` with varying release thickness ranging from 1 m to 3.5 m in 0.5 m increments, resulting in 90 total model runs. Release areas for the idealized snow slides were defined to stretch from the highest point of the profiles/topographies to the onset of the transition between release and runout area (first point where curvature changes along the profile). Model settings from Tab. 1 were used for all simulations, DEM resolution was set to 2m.

Resulting model outputs were analyzed with respect to modeled runout lengths and peak pressures. Specifically, the main analyzed metrics focused on the modeled peak pressures at the β_{10° point (ppr$^{max}_{\beta_{10^\circ}}$ [kPa]) and runout distances from this point to the point, where modeled peak pressures drop to 0 kPa (Δ^{max}_{s} [m]). Figure 2 shows an example for the analysis of model results for the topography with 60 m vertical drop and 40° release area inclination.

2.6. Formulation of surrogate models

Based on the analyzed model results, previous rapid assessment tools used for snow slides (cf. Granig et al. (2019), p.8) and iterative discussions within the project group, we worked on the formulation of two rapid assessment tools. The main idea was to correlate the target variables ppr$^{max}_{\beta_{10^\circ}}$ and Δ^{max}_{s} to the explanatory variables `release thickness [m]`, `vertical drop [m]`, and `average release area inclination [°]`. For the formulation of the surrogate models, these explanatory variables could be extracted from the model runs' initial and boundary conditions. For the application of the same models, the same variables can be directly measured in the field or estimated from maps and digital elevation models.

3. RESULTS & DISCUSSION

3.1. Correlation analysis

Figure 3 shows the Spearman rank correlation between the two target variables (ppr$^{max}_{\beta_{10^\circ}}$, Δ^{max}_{s}) and the three explanatory variables (`release thickness`, `vertical drop`, `average release area inclination`) obtained for the 90 model runs. We can observe that the release thickness shows a strong positive correlation with both ppr$^{max}_{\beta_{10^\circ}}$ and Δ^{max}_{s} in our results, meaning that higher release thicknesses lead to increases in both modeled peak pressures at the β_{10° point and runout distances measured downslope from this point. The correlations of release area/track incline and vertical drop with the two response variables show an inverse behavior. While steeper release areas and tracks are correlated with higher modeled peak pressures at the β_{10° point, they show a slight negative correlation with modeled runout lengths. Conversely, higher vertical drop heights show a slight positive correlation with modeled runout lengths while being slightly negatively correlated to modeled peak pressures at the β_{10° point. All correlations except the one between drop height and peak pressure at the β_{10° point are statistically significant at the level of $p < 0.05$.

3.2. Simplified surrogate models

Based on the analysis of model results we proposed two simplified rapid assessment tools for expected peak pressures at the β_{10° point and runout distances downslope from this point.

The β_{10° point was selected as a reference point in our analysis and for the surrogate models, since it is firmly established in the operational natural hazard management context in Austria and potential users are familiar with identifying it in the field and on maps. Graphical, diagram-oriented representations of the assessment tools were likewise adopted because they provide a practical and intuitive evaluation framework in both field and desktop settings.

Figure 4 shows the proposed diagram for estimating runout lengths downslope from the β_{10° point. The influence of all three statistically significant explanatory variables is considered in the diagram. After selecting a representative release thickness, potential users of the tool can fine-tune the range of expected runout distances by selecting corresponding values for track/release area inclination and vertical drop. Values of the explanatory variables that fall between the discrete data points portrayed can be visually interpolated or conservatively rounded up to the next discrete value.

Figure 5 show the proposed diagram for estimation of expected peak pressures the β_{10° point. It features a contour plot, where expected peak pressures at the evaluation point can be selected based on track/release area incline (x-axis) and release thickness (y-axis). Based on the results of the correlation analysis and visual inspection the diagram simplifies to the 60 m vertical drop case. While drop height was not identified as statistically significant predictor of ppr$^{max}_{\beta_{10^\circ}}$ in the correlation analysis it still explains some of its variance. Expected peak pressures at the β_{10° point decreased

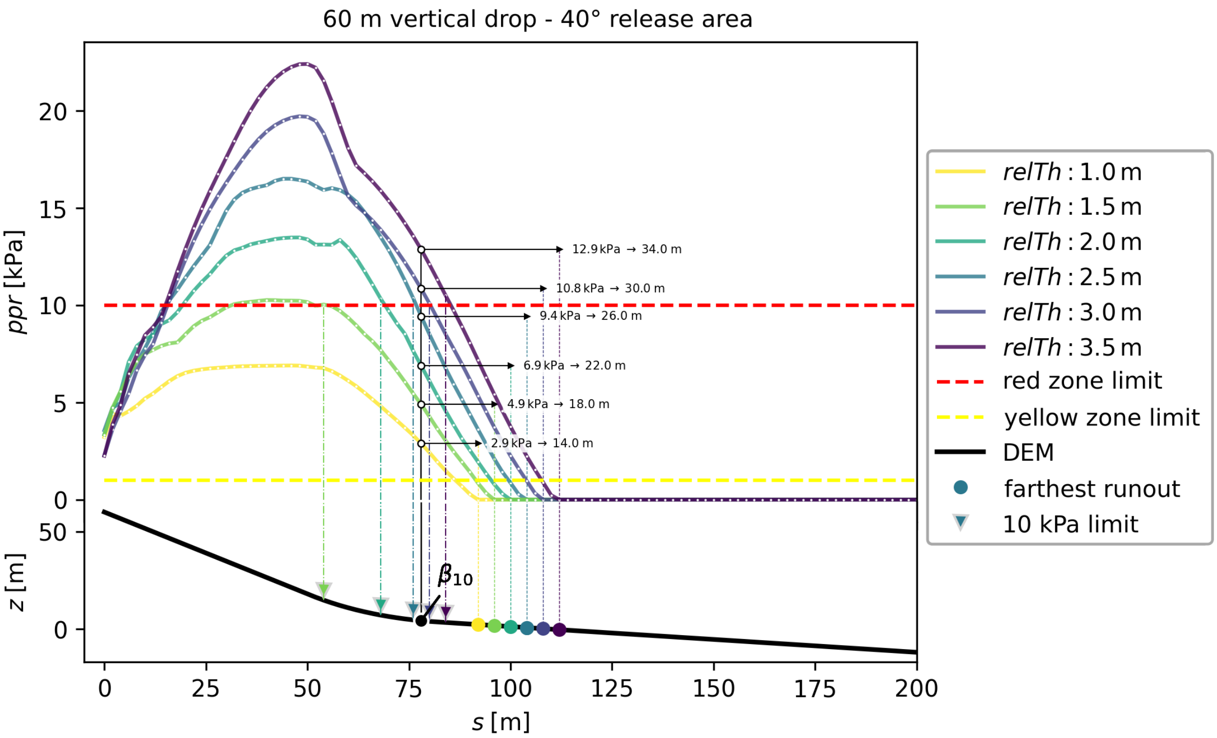


Figure 2: Example of the automated analysis of `com5SnowSlide` simulations with varying release thickness for one of the 15 idealized topographies. The lower part of the figure shows the longitudinal topographic profile, while the upper part depicts the corresponding peak pressures along the profile for the different release thicknesses. For each simulation, the maximum peak pressure at the β_{10° point ($\text{ppr}^{\text{max}}_{\beta_{10^\circ}}$ [kPa]) and the maximum runout length measured in the flow direction from this point (Δ_s^{max} [m]) were extracted.

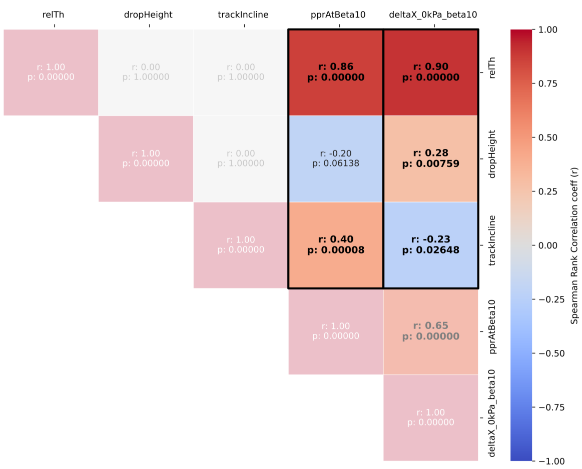


Figure 3: Correlation matrix showing spearman rank correlations between the three explanatory and two target variables. Statistically significant correlations at $p < 0.05$ are marked in bold.

by approximately 0.3 kPa for every additional 10 m of vertical drop relative to the 60 m reference case, and increased by a similar magnitude for every 10 m reduction in vertical drop. A simplified way to account for this additional variance introduced by vertical drop deviating substantially from the 60 m case could be to round identified data-points up or down to the next integer isobar accordingly.

For both rapid-assessment diagrams, uncertainty in the estimation of the required explanatory variables can be directly represented and communicated by marking corresponding circular or elliptical regions on the diagrams rather than pinpointing individual values. In doing so, the simplified nature of the proposed rapid-assessment tools is explicitly acknowledged, while flexibility for the incorporation of local expert knowledge and site-specific considerations is retained.

3.3. Evaluation for selected case studies

In order to evaluate the practical applicability and potential application limits of the proposed surrogate rapid assessment tools we compared them against slope-scale numerical simulations with `AvaFrame/com5SnowSlide` for nine snow slide re-

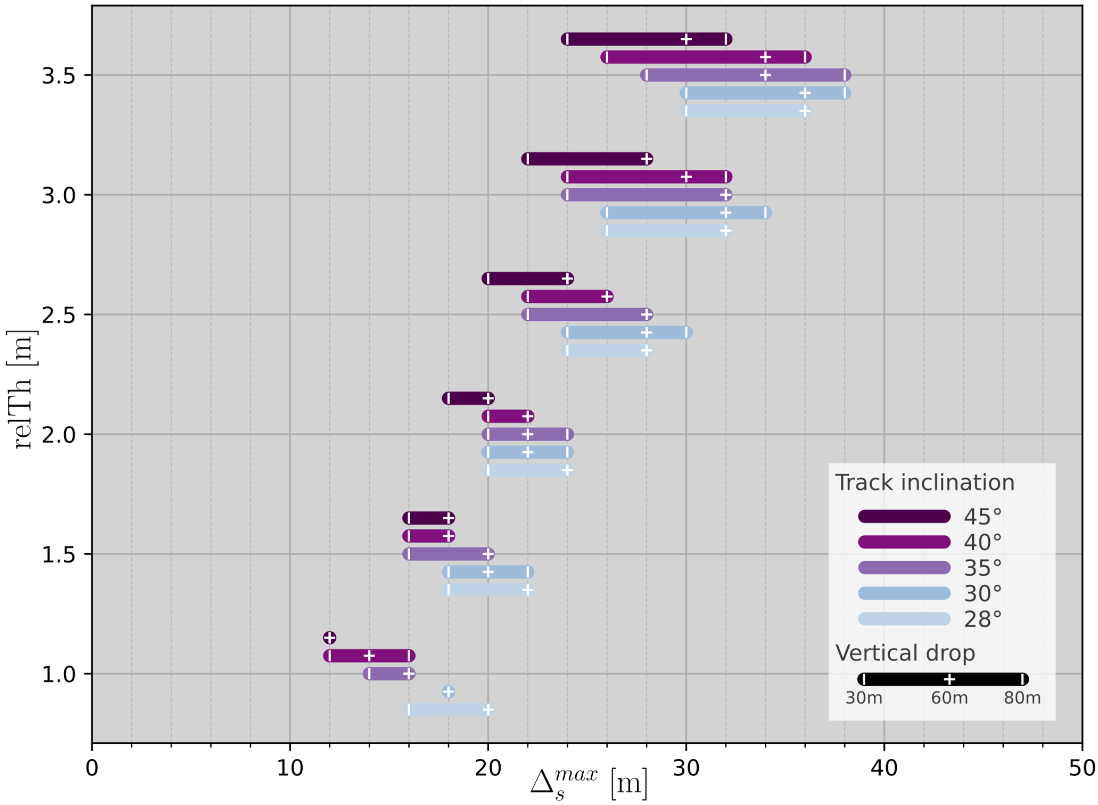


Figure 4: Simple surrogate model for estimating runout distance from the β_{10° point in m based on release thickness relTh [m] (x-axis), inclination of the release area (color code) and vertical drop (position along the bars).

lease areas at five study sites.

For eight of the nine compared release areas runout distances estimated with the proposed diagrams were slightly more conservative compared to the results of the numerical simulations, but generally did not exceed simulated runout lengths by more than approximately 10 m. Only for one case estimations with the diagram yielded substantially longer runouts (≈ 20 m) than the numerical model.

The peak pressures predicted by the simple diagram at the β_{10° points or respective lines were in good agreement with the results of the numerical simulations for the same snow slides, with the exception of the aforementioned case.

Figure 6 shows exemplary results of the comparison between numerical simulation and prediction with the simplified surrogate models for three release areas in two of the study sites in Tyrol, Austria. The mapped β_{10° lines and corresponding runouts predicted by the simplified diagram are depicted by the dashed black and red lines respectively along with the modeled maximal peak pressures derived from the numerical simulations. For both examples maximum runout lengths and expected peak pressures estimated with the simple diagrams are in good agreement with results of the numerical simulations. Larger deviations can only be observed in areas where cross-slope curvature differs from the simplified planar slope assumption adopted in our study.

3.4. *Application limits*

While these results are encouraging, several limitations related to the adopted methodology and underlying data should be acknowledged.

One limitation arises from the fact that the rapid assessment tools were developed based on planar snow slide topographies and did not account for the effect of mitigation measures. Larger deviations have to be expected in more complex terrain. Likewise, the effect of mitigation measures, buildings, walls or other obstacles must be evaluated with separate methods.

Similarly, the application of the surrogate models in the presented form is limited to cases, where a β_{10° point/line can be identified at the slope base. As apparent from the analysis in this study and similarly observed by other authors (e.g. Toft et al. 2023), the identification of a β_{10° point is not always straightforward and sometimes impossible,

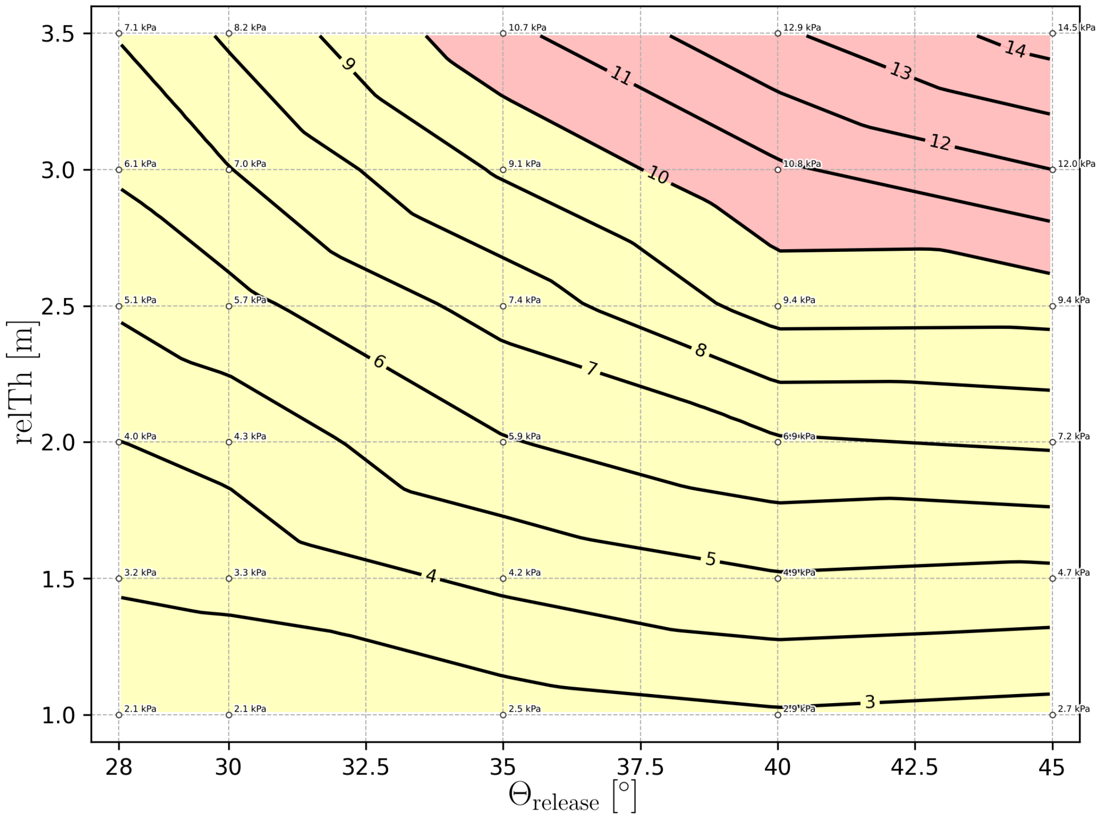
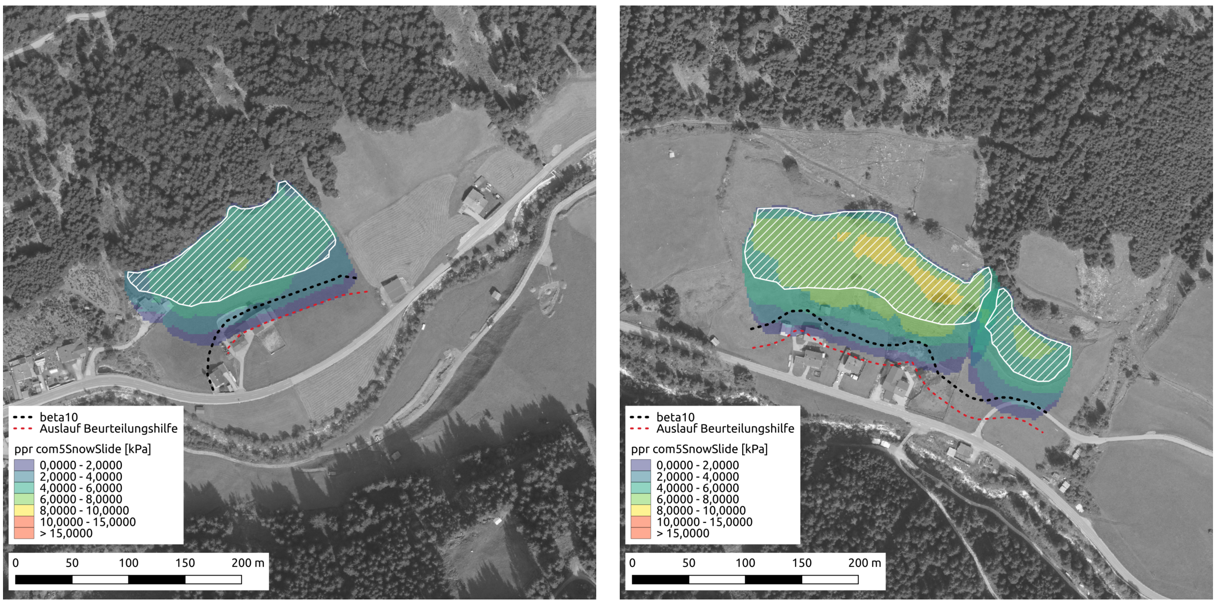


Figure 5: Simplified surrogate model for estimation of peak pressure at the $\beta_{10°}$ point. ppr$^{max}_{\beta_{10°}}$ [kPa] can be estimated from release area inclination θ_{release} in ° (x-axis) and release thickness relTh in meters (y-axis). Discrete data points of the 30 simulations used for interpolating the contours are shown for reference.



(a) site "Muchiler", Gries i. Sellrain
ppr$^{max}_{\beta_{10°}}$ ≈ 5 kPa, Δ^{max}_{s} ≈ 16 m

(b) site "Muhrenhöfe", Gries i. Sellrain
ppr$^{max}_{\beta_{10°}}$ $\approx$ $3-4$ kPa, Δ^{max}_{s} $\approx$ $15-18$ m

Figure 6: Two examples for the comparative evaluation between `com5SnowSlide` model results and applications of the simplified surrogate models. The $\beta_{10°}$ reference lines are depicted in black, the predicted runout lines with the simple surrogate model are shown in red. The sub-captions for each site also list the runout lengths and peak pressures predicted with the simplified graphs. Orthophotos courtesy of `basemap.at`.

because deposition zones for smaller avalanches and snow slides can be located in terrain considerably steeper than $10°$. While the presented diagrams could be readily extended to alternative reference points (e.g. $\beta_{15°}$ or $\beta_{20°}$), this would come at the cost of added complexity.

Another limitation relates to the regional context of the underlying data and study setup. The surrogate models are based on Austrian data and reflect the specific terminology, concepts, and practical requirements of Austrian natural hazard management. Consequently, their direct applicability to other regions may be limited. Nevertheless, the underlying methodology could be transferred to other areas given suitable regional data and comparable application context.

4. CONCLUSION & OUTLOOK

Our results indicate that the developed rapid assessment tools enable a quick and conservative assessment of expected snow slide runout lengths and impact pressures in practical settings.

The surrogate models require limited input parameters (location of $\beta_{10°}$ point/line, release thickness [m], track inclination [°], and vertical drop [m]), that can be readily assessed in GIS-applications or in the field. Results are in comparable ranges to dedicated simulations with `AvaFrame/com5SnowSlide` and provide conservative and robust initial estimates. However, the presented tools do not substitute detailed numerical modeling and/or local expertise and users must evaluate whether any of the application limits discussed above may apply.

Building on this foundation and utilizing additional open-source tools available in OpenNHM (`opennhm.org`), future efforts could extend the validation of the methods to a larger set of case studies or focus on expanding the scope of application to regional-scale snow slide susceptibility assessment (cf. Egger et al. 2018).

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