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APALI – Avalanche Probability Along Linear Infrastructure

Abstract

To secure linear infrastructure in the most cost-efficient manner, hazard hot-spots need to be known not only with regard to the intensity of possible events but also their probability. Traditional hazard mapping methods rely on analysis of historical records—which are often missing or scarce—or on experts' subjective judgment. Either approach is time-consuming and expensive. The hazard mapping system NAKSIN for snow avalanches contains a module for estimating avalanche release probability automatically using topographical, weather and forest data and calculates avalanche run-out for one target return period. This Note outlines how NAKSIN can be modified to produce maps of avalanche hit probability and optionally probability distribution functions of impact pressure and/or flow velocity. While the needed modifications are easy to implement, the NAKSIN module for release probability requires improvements to produce more reliable estimates in areas with continental climate.

Contents

1 Introduction

In Norway and other mountainous countries, linear infrastructure such as railway lines, roads and power lines can be threatened by gravity mass flows (GMFs) like snow avalanches, rock fall and rock avalanches, debris flows and shallow landslides at many places. Even if the risk at a single location is moderate to low, the total risk to, say, a car driving a long distance may become considerable. Mitigating the hazards at many points may be very expensive. Therefore, it is important in the planning phase of large infrastructure projects to obtain a good understanding not only of the intensity of different hazard types along the line but also of the annual *probability* of hazardous events. If the probability distribution function (PDF) of a hazard is known in terms of the hazard intensity, the individual and societal *risk* can be calculated by assuming suitable vulnerability functions and exposure values.

Traditional hazard mapping methods for GMFs focus on calculating the run-out area and often also the spatial distribution of intensity for predefined scenarios. Legal requirements for hazard protection typically prescribe maximum acceptable intensities for a few nominal return periods (e.g., 30, 100 and 300 years in Switzerland) or minimum return periods for different categories of buildings (in Norway, 100 years for garages, boat houses and similar structures, 1000 years for dwellings of limited size and 5000 years for large residential or public buildings). In Norway, the scenarios corresponding to events of the mentioned return periods are (subjectively) estimated by experts using historic, topographic, climatic and vegetation data. In contrast, the Swiss guidelines for snow avalanches—used in adapted form in the other Alpine countries—effectively assume that any potential release area has a return period of less than 30 years and determines the fracture height according to climate region, altitude, wind exposure and return period.

When managing natural hazards along linear infrastructure, neither of these methods is adequate because the probability of hazardous events plays a central role. The Norwegian approach may be able to provide estimates of the return period for GMFs in each segment of a road, but the necessary manual work is prohibitive in large projects. If the Swiss method were extrapolated to return periods less than 30 years, the hazard would be greatly overestimated. Thus one needs a probabilistic approach that automatically estimates the return periods of GMFs in different paths.

Methods for probabilistic hazard mapping of snow avalanches have been developed since at least the late 1990s. The efforts have been concentrated on the run-out calculation: Assuming PDFs for the fracture depth and the friction parameters, a run-out model is applied many times in a Monte Carlo process, counting the number of times each computational cell is hit. If the input PDFs are interpreted as expressing our lack of knowledge of the input parameters for a given return period, the resulting map represents the corresponding uncertainty of the hazard zone (disregarding systematic errors from model shortcomings, estimation of the relase area, etc.). If the PDFs reflect the variation of these parameters in Nature, the resulting map shows the (relative) probability of avalanche run-out to each point. To obtain a map of local return periods, the normalization of the input PDFs (amounting to the number of avalanche releases per year) must be known. This is the type of information that is needed when managing natural hazards along linear infrastructure. As indicated above, it can be supplemented with vulnerability and exposure relations for quantitative risk assessment (QRA).

There are three main reasons why this approach is not standard practice in hazard management yet:

1. In administrative matters, binary answers are requested from the authorities: "Is it safe to build here – yes or no?" There is simply no place for fuzziness in administrative decisions.
2. There is no consensus among avalanche researchers and experts about the PDFs to use for the friction parameters; moreover, they depend on the specific run-out model.
3. Even more conspicuous is the lack of a method for *calculating* release probabilities, which would be a prerequisite for calculating the probability of a flow reaching a given point.

While the first reason is not relevant in the present context, the second is of concern. It can partially be circumvented, however, by exploiting empirical knowledge of reasonable parameter ranges for avalanches with different return periods. An efficient in-house code for probabilistic run-out calculations is available at NGI. Finally, there is now a candidate method and code for estimating release probabilities for snow avalanches in an objective and automatic way. Combining these elements, one can design a system for efficiently calculating snow avalanche probabilities and intensities in extended areas, and in particular along linear infrastructure. The rest of this Note details the concept, lists the main changes to apply to available codes, and discusses briefly which problems might arise in the development phase.

2 The starting point – NAKSIN and Voellmy-pro

Avalanche release probability – NAKSIN. Since 2015, NGI has been developing the system NAKSIN (Nye AktsomhetsKart for Snøskred I Norge) for (semi-)automatic generation of avalanche hazard indication maps, abbreviated as AHIMs in the following (Issler *et al.*, 2020, 2023). A run of NAKSIN proceeds through the following steps, each of them corresponding to a module of the Python 3 code:

Main Interpret the set-up file, set global variables, sequentially launch the following modules, handle error messages if necessary.

Module 1 Select a sufficiently large area of interest (AoI), produce the corresponding computational grid from the DTM and clip the gridded forest data for the AoI from a nation-wide data set.

Module 2 Determine the potential release areas (PRAs) from geometric criteria (slope, size, curvature, shape).

Module 3 Estimate the release probability for each PRA, taking into account terrain, climate and forest cover. The release depth of avalanches with return period T equal to a user-defined target return period T_t is determined and stored.

Module 4 Carry out numerical simulations with the quasi-3D run-out model MoT-Voellmy (Issler, 2023).

Module 5 Combine the calculated avalanche run-out areas from all paths into the AHIM.

Avalanche run-out probability – Voellmy-pro. NGI has also developed an extension of MoT-Voellmy, called Voellmy-pro, that uses a simplified variant of Latin Hypercube Sampling and parallel processing for efficient probabilistic run-out calculations. Voellmy-pro needs raster files for the mean fracture depth $\bar{h}_0(\mathrm{x})$, mean snow-cover shear strength $\bar{\tau}_c(\mathrm{x})$, and mean friction parameters $\bar{\mu}(\mathrm{x})$, $\bar{k}(\mathrm{x})$; in addition, the user has to specify cumulative PDFs for these four variables in the form of factors

$$f_\Phi \in [f_{\Phi,\mathrm{min}}, f_{\Phi,\mathrm{max}}], \quad \text{with} \quad \Phi \in \{h, \tau_c, \mu, k\}, \tag{1}$$

such that the expectation value of f_Φ is 1 for each Φ. Voellmy-pro first generates the requested number of samples $(f_h, f_\tau, f_\mu, f_k)$ following the specified cumulative PDFs and then launches multiple runs of the flow solver of MoT-Voellmy. For each run ℓ, the input parameters are set as

$$h_0^\ell(\mathrm{x}) = f_h^\ell \cdot \bar{h}_0(\mathrm{x}) \tag{2}$$

and analogously for τ_c, μ and k.

Each of these runs generates a raster of the maximum flow/deposit depths, $h_{\mathrm{max}}^\ell(\mathrm{x})$ attained in each computational cell in the course of the simulation. If desired, similar rasters for the maximum pressure and/or the maximum velocity can additionally be written. Where $h_{\mathrm{max}}^\ell(\mathrm{x})$ exceeds a user-specified threshold (typically 0.1 m), the count of hits in the corresponding cell is increased by 1. If the total count of hits in cell (i, j) after N simulations is n_{ij}, the relative run-out probability at that point is n_{ij}/N. Assuming the release probability per year to be P_{rel}, the frequency of avalanches hitting the point (i, j) is

$$P_{ij} = P_{\mathrm{rel}} \cdot \frac{n_{ij}}{N}. \tag{3}$$

3 General concept of APALI

APALI as a combination of NAKSIN and Voellmy-pro. By replacing the function call to MoT-Voellmy with a function call to Voellmy-pro in NAKSIN, one achieves, in principle, fully probabilistic hazard mapping, calculating the annual avalanche probability for each cell of the computational grid. This raster file can easily be profiled along a desired route in standard GIS software like QGIS, GRASS, SAGA or ArcGIS Pro.

If one aims for QRA, additional information about the event intensity must be collected and processed in both Voellmy-pro and NAKSIN:

- In each run-out simulation, Voellmy-pro must write the maximum pressure and/or velocity in each cell into a three-dimensional array, which it passes to NAKSIN at the end of the simulations for that avalanche path.
- For each avalanche path in the study area, NAKSIN must append the pressure values measured in each cell to the list of values in the corresponding cell of a global 3D array so that cells endangered by more than one path are handled correctly.
- The values in each cell of the global 3D array must be sorted and approximate cumulative PDFs of pressure or velocity extracted. These can then be used in risk analyses.

Necessary changes in NAKSIN and Voellmy-pro. In the initial development phase, the extensions for QRA may be left out. The following changes in the NAKSIN modules are required for probabilistic hazard mapping:

Main module:

- Test for presence of the Voellmy-pro executable.
- Adapt the routine for parsing the set-up file to new file content.
- Add new variables to the store of global variables.

Module 3 – Release probability:

- For each “avalanche release”, record not only the fracture depth but also the temperature, the snow depth H_S, the new-snow depth H_N and its density, and the shear strengths of the slab and weak layer. (These snow properties can be used to constrain the friction variables for the run-out calculation.)
- After the Monte Carlo trials, sort the “avalanche releases” according to fracture depths as in NAKSIN and then create a table representing the cumulative PDF for the fracture depth in this path.
- For each probability interval of the fracture-depth table, fit the recorded temperature and shear strength values to beta distributions and record their parameters (minimum and maximum values, shape parameters) in the table.

Module 4 – Run-out calculation:

- Adapt the run configuration file for Voellmy-pro
- Modify the algorithm calculating $\mu(\mathrm{x})$ and $k(\mathrm{x})$.
- Change the command launching the flow simulations.
- Modify the treatment of error conditions.

Module 5 – Map assembly:

- Add avalanche hit probabilities (real numbers) instead of hit counts (integers).
- For QRA applications, add the cumulative PDFs for pressure and/or velocity from all avalanche paths reaching a given grid cell.

4 Anticipated critical issues

Shortcomings of the NAKSIN module `release_area`. Most avalanche events in Nature release only from a sub-area of the PRA, which is important for the lateral and longitudinal reach of the avalanche as well as the velocity and pressure in the run-out zone. However, NAKSIN currently uses the entire PRA in the modules `release_prob` and `runout`. The present approach is conservative but may lead to hazard areas that are significantly larger than necessary.

An algorithm for finding the most likely sub-area of a PRA under given snow and weather conditions has recently been proposed (Issler, 2022) but has not been tested yet. If it is found to be promising, it can be used in APALI only after some adaptations of the NAKSIN module `runout` and Voellmy-pro.

Shortcomings of the NAKSIN module `release_prob`. NAKSIN has so far been mainly applied for creating hazard indication maps referring to buildings in security class S2, i.e., the target return period was set at $T_t = 1000$ y. In probabilistic hazard mapping—and even more so when it is directed at linear infrastructure—small but frequent events are relevant as well. Tests of NAKSIN with $T_t \leq 100$ y have shown that (i) release frequency tends to be underestimated by up to two orders of magnitude in areas with continental climate and little snow and that (ii) the list of fracture depths contains many synthetic events with non-physical fracture depths of less than 1 cm.

Both shortcomings will have a strong effect on the results from APALI, which cannot be expected to be realistic before this has been fixed in the module `release_prob`. This is an urgent task in the further development of NAKSIN; furthermore, it is likely that both problems have the same root. APALI can, however, be developed before this issue is resolved; any changes in the NAKSIN module will port to APALI with minimal or no changes to the APALI-specific code parts.

Performance considerations. Probabilistic hazard mapping is much more computation-intensive than the traditional method. Compared to NAKSIN, APALI must do some extra work in the module `release_prob` to determine the cumulative PDF for the fracture depth, particularly if the extensions for QRA are implemented. While the run-out calculations tend to consume only a moderate fraction of the total computing time in NAKSIN, they will dominate in APALI. Limited experience from an application of Voellmy-pro suggests that satisfactory results may be obtained with as few as 24 simulations per avalanche path in many cases, but capturing extreme avalanche run-out may require between 100 and 1000 simulations. Extensive testing will be needed to find a good compromise.

While the flow solver of MoT-Voellmy is very fast in not too rough topographies, numerical instabilities can force it to use very short time steps in complicated terrain with abrupt changes of curvature. This problem will hopefully be mitigated in the near future through an improved flow solver.

Both NAKSIN and Voellmy-pro use parallel processing to improve their performance drastically on workstations with many processor cores. In APALI, the question arises how to allocate cores between the Python 3 modules from NAKSIN and the C code from Voellmy-pro. On the one hand, a larger fraction of the program is parallelized in Voellmy-pro than in NAKSIN, and the OpenMP library for C may scale better with the number of processes than the Python module `multiprocessing`. This appears to favor running NAKSIN as a single-core process and letting Voellmy-pro use all cores. On the other hand, code pieces in Voellmy-pro that require exclusive access to files on disk may become bottlenecks. This should be less of a problem with the NAKSIN code; moreover, larger parts of the code could be parallelized. It is possible to specify the maximum number of parallel processes independently in NAKSIN and Voellmy-pro, so this question can be approached “experimentally”.

PDFs of input parameters. Finding realistic PDFs for the input parameters is the central problem of probabilistic run-out calculations. There is no generally accepted answer to the problem, which moreover would strongly depend on the numerical model that is used in the analysis.

Voellmy-pro contains four parameters that are varied independently according to the specified cumulated PDFs, namely the mean values of the fracture depth, $\bar{h}_0$, the snow-cover shear strength, $\bar{\tau}_c$, and the friction parameters $\bar{\mu}$ and $\bar{k}$. There should, however, exist important cross-correlations between them:

- First, a large fracture depth is not possible without a considerable shear strength of the slab and the weak layer. This correlation is reflected in the data on each “avalanche release” stored by NAKSIN. Thus, one may use the stored value as $\bar{\tau}_c$ and perturb it with a narrow beta distribution. Under these conditions, the exact choice of the PDF influences the run-out only weakly.
- In turn, the shear strength and compressibility of snow depend strongly on the snow density. According to a recently proposed theory on fluidization (Issler, 2017), excess pore pressure is generated when an avalanche flows over the snow cover and destroys its texture. The excess pore pressure reduces the effective stress at the bottom of the flow and thus the effective friction coefficient. This suggests choosing $\bar{\mu}$ and $\bar{k}$ as negatively correlated with the ratio $g\bar{h}_0/\bar{\tau}_c$ and, possibly, as positively correlated with the simulated temperature of that “event”, which is to be stored by `release_prob`.

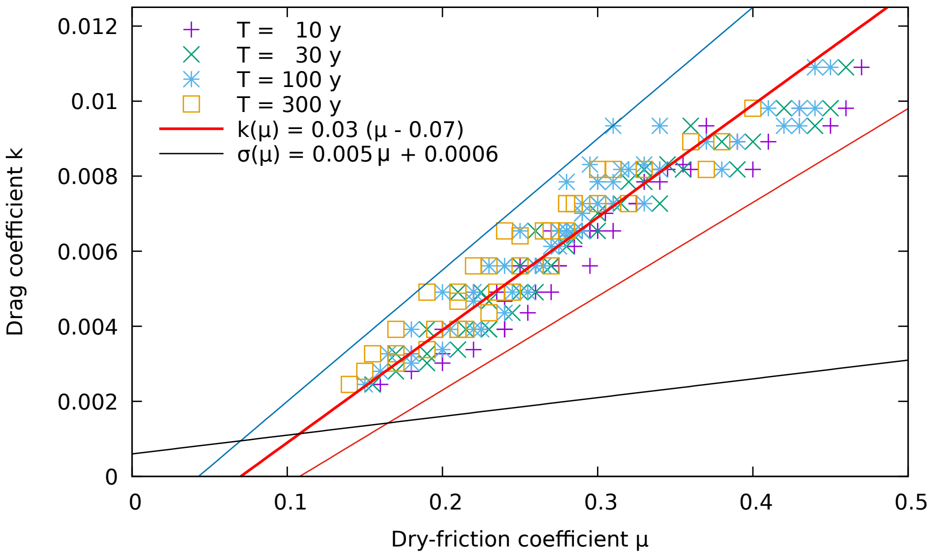

Figure 1 The Voellmy drag coefficient k as a function of the dry-friction coefficient μ in SLF's calibration of RAMMS::AVALANCHE. That table contains four return periods (10, 30, 100, 300 y), four avalanche-volume categories, four terrain categories, and three altitude categories. The plot suggests that the variability of k may be modeled as a linear function of μ plus a random component drawn from a beta distribution with a standard deviation depending linearly on μ.

> It is reasonable to assume that the Voellmy drag coefficient k is positively and quite strongly correlated with the dry-friction coefficient μ. SLF's calibration for the code RAMMS::AVALANCHE (Bartelt *et al.*, 2017), which is also applied to MoT-Voellmy in NAKSIN, reflects this as well (Fig. 1). This suggests that the stochastic variability of μ and k can be assumed fairly small if the strong correlation with τ_c and the temperature is accounted for. The uncertainty in these PDFs will only weakly influence the PDF of the run-out area.

The considerations given above indicate that the fundamental driver of the variability of the run-out of snow avalanches in a given path is the variability of the shear strength of the snow, which in turn sets upper and lower bounds on the fracture depth and the Voellmy friction coefficients. The proposed fluidization theory shows qualitatively how μ and k should depend on the snow-cover properties. Once this physical constraint has been taken into account, the specific form of the assumed PDFs becomes less important because they should be fairly narrow. The way in which Voellmy-pro creates samples will need a few modifcations. During the development of APALI, different specific dependencies of $\bar{\mu}$ on $\bar{\tau}_c$ have to be explored and some uncertainty will remain. Nevertheless, there is reason to hope that practically useful results can be obtained because these uncertainties afflict the absolute values of avalanche probability much more than the relative differences within a path or between different paths.

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