AUTOMATIC DYNAMIC MODELING-AN EXAMPLE OF ITS APPLICATION IN AN OPERATIONAL SETTING IN NORWAY

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ABSTRACT: The county road Fv. 53 at Tyin (Norway) is an important road for the inner parts of the Sogn region and especially the local community in Årdal. In winter time, it is regularly exposed to avalanche hazards. An operational avalanche control service is present, which includes daily avalanche forecasts and using remote avalanche control systems (RACS). To support the local forecasting team, a model chain has been developed and implemented in which numerical snowpack modelling is coupled to avalanche dynamics simulations to assess avalanche risks. The primary system output is an assessment of snow cover stability as well as avalanche size and runout. Based on measurements from automatic weather stations, the temporal evolution of the snowpack is simulated using the SNOWPACK model. The SNOWPACK model provides snowpack stability estimates and, based on the weak layer depth, potential fracture depths and snowpack properties of the slab. The spatially distributed model Alpine3D allows to account for complex terrain features such as radiation effects. This information is used to provide the initial conditions for the avalanche dynamics model RAMMS for predetermined avalanche paths. The model chain was run for 14 different avalanche paths which could affect the 9 km road section at Tyin and are relevant for the operational forecasting. Around 100 avalanches were triggered using the installed RACS in the winters 2016/17. This dataset was used to verify and calibrate the models. As wind drift is a major challenge in the Tyin operation, new algorithms were tested to account for wind transport. The properties of the entrained snow, which is an important factor to determine avalanche runout, are also accounted for. The system in which real-time snow cover simulations are combined with avalanche dynamics simulations is a novel approach to provide avalanche forecasters with a new source of objective information to support the avalanche control team in their decision making and risk management.

KEYWORDS: numeric modeling, avalanche dynamics, snowcover modeling, risk assessment

1. INTRODUCTION

The county road Fv. 53 at Tyin (Norway) is an important road for the inner parts of the Sogn region and especially the local community in Årdal. A large part of the road is located above tree line, which makes it very exposed to winter storms and avalanche hazards. Although the avalanche paths threatening the road are not very large (release areas 100 – 300 m. above the road), the large, rather flat area west of the road acts as a very large fetch and in combination with frequent events of strong westerly winds, the road was exposed to significant avalanche danger on regular bases. For the first time, a Norwegian road is protected with an operational avalanche control service that includes daily avalanche forecasts and using remote avalanche control systems (RACS), consisting of 14 control towers. Fig. 1 shows an overview of the area.

To effectively use avalanche control systems, it is important to know how the snow cover stability develops. During night or adverse weather conditions, this may be difficult to assess visually. Furthermore, visiting release zones for a stability assessment is often dangerous. The use of numerical snow cover modelling for a snowpack stability assessment has therefore seen an increased interest over the recent years (e.g., Wever et al., 2016, Gaume et al., 2017). Here, we present a model chain in which spatially distributed numerical snowpack modelling is

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coupled to avalanche dynamics simulations to assess avalanche risks. It extends the approach by Wever et al. (2018) for wet snow avalanches to also include dry snow avalanches.

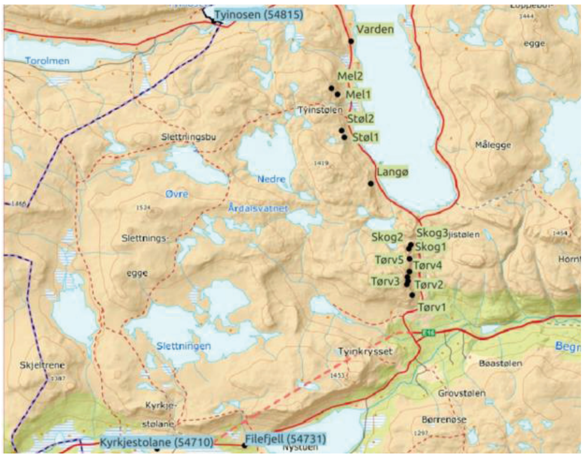

Fig. 1: Map of the area, showing the meteorological stations in blue and the avalanche control towers in green along the road Fv. 53 at Tyin (Norway) in red.

2. DATA and METHODS

2.1. Snow cover simulations

The Alpine3D model performs distributed snow cover simulations (Lehning et al. 2006), using the Swiss, detailed physics-based SNOWPACK model (Bartelt et al., 2002). The main measurement site to drive the simulations is the Kyrkjestolane station, at 980 m above sea level (a.s.l.), operated by the Norwegian Meteorological institute. This site provided air temperature, relative humidity, wind speed and direction, snow depth, precipitation from a heated rain gauge, and incoming shortwave radiation. Furthermore, the Filefjell and Tyinosen measurement sites, operated by Statens Vegvesen, provide a more limited set of parameters (air temperature, relative humidity, wind speed and direction and snow depth only). To accurately describe gradients in temperature and wind speed with elevations, an automatic weather station presents at the Langø tower, operated by Wyssen, was used. Finally, the GFS weather model was used for incoming longwave radiation, to gap fill meteorological measurements and to perform simulations for 48 hours in the future.

Using the MeteoIO preprocessing library (Bavay and Egger, 2014), the meteorological point data was translated into interpolated fields by considering the underlying digital elevation model. For example, precipitation, temperature, relative humidity and wind speed were interpolated by first determining the lapse rate and then interpolating the residues over the model domain. For incoming shortwave radiation, the diffuse part was homogeneously distributed over the grid, whereas the direct part was interpolated by taking into account the slope aspect and angle relative to the solar position. For precipitation, the Winstral algorithm (Winstral et al., 2002) was additionally applied to redistribute snow from wind exposed areas to sheltered areas, to describe the effect of wind redistribution by wind. Furthermore, snow drift calculated by the SNOWPACK routines inside the Alpine3d model (Lehning and Fierz, 2008) was also used to erode snow from wind exposed areas and redistribute it in wind sheltered areas.

The snow cover simulations provide spatially explicit information about, among others, snow depth, snowpack stability (Lehning et al., 2004), snow density and snow wetness (Wever et al., 2018). Weak layers and potential fracture layers can identified by analysing the simulated snow profiles.

2.2. Avalanche Dynamics simulations

As the snowpack properties and fracture depth do not necessarily indicate the consequences of a release (in terms of avalanche size and runout distance), simulations were performed using the RAMMS-Extended model (Christen et al. 2010, Vera Valero et al., 2016). Based on the simulated snow cover conditions, the most likely release scenario was determined, described by release depth, and snow properties of the slab (temperature, snow density, liquid water content). For each avalanche control tower, a typical release area was depicted based on terrain analysis by expert judgment. This release area is kept constant for the whole season. Based on historical avalanche records, the RAMMS-Extended parameter settings were determined (Vera et al, 2018).

- The grid resolution: the resolution was set to 3 m for medium to small avalanches and 5 m for the avalanches which release fracture was estimated to be bigger than one meter. Note that a resolution higher than 3 m is not necessarily producing more accurate simulations, as the lower grid resolution can be considered to describe the smoothing effect of the snow cover on the summer terrain.

- Flowing density was set to 400 kg/m$^{3.}$ Bigger avalanches (>1 m release depth) reach higher dissipative forces and higher compaction of the flowing snow (granules) and the flowing density was set to 450 kg/m^3 for these cases.

- Friction parameters (Mu, Xi, Cohesion): These three parameters in RAMMS-Extended depend on snow temperature and avalanche fluidization but the empirical functions have an initial parameter that we keep always constant for all cases, (Vera et al, 2016).

- The release and erosion data is obtained from the SNOWPACK and A3D simulations. The data are fracture and erosion depth, snow density, snow temperature and snow water content along the avalanche path.

- The energy parameters account for the degree of fluidization of the avalanche. They depend on the terrain and on the snow temperature. As in the friction parameters RAMMS uses empirical functions which contain parameter. We use a slightly higher fluidization parameter of 0.08-0.09 for the big avalanches (>1 m release depth), and 0.06-0.07 otherwise.

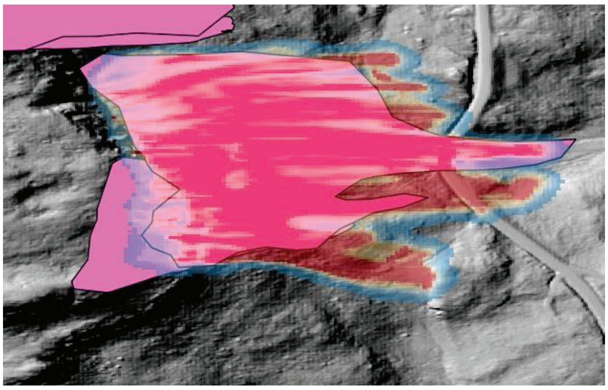

Fig. 2: With a correct estimation from the release area (big scenario) and the calibrated set of parameters RAMMS_extended was able to back-calculate the avalanche occurred.

2.3. Field observations

The field observations of snow cover properties as well as documentation of when and where successful avalanche control was carried out, forms a crucial part of the operations and can be used to validate the model chain results. The field observations consisted of regular snow profiles and documenting the outline of both artificially triggered as well as naturally occurring avalanches. Furthermore, an estimate of fracture depth, as well as snow properties forming the fracture were recorded. However, it proved difficult to correctly assess snow properties from a distance and visiting the release areas was often too dangerous.

2.4. Operational model chain

The model chain was run 4 times per day, at 00, 06, 12 and 18 UTC, by first running the Alpine3D model up to the current time step with measured meteorological data, and then 48-72 hours in the future by using the GFS model forecast. Afterwards, the forecasted snow cover state in the release areas below the avalanche control towers was analysed to find the lowest value of the structural stability index (Lehning et al., 2004). Slab thickness, temperature, density and wetness were derived from the snow cover state and initialization files for the RAMMS-Extended model were created. Then, the RAMMS-Extended model was run for each avalanche path.

As avalanche controls are performed multiple times per avalanche path per snow season, the simulation of the snow cover development below the tower has an additional complication from the effect of earlier releases. One of the most important aspects is the snow depth in the release area, which is reduced due to multiple releases during a snow season. This in turns may also affect the snowpack layering and liquid water percolation in spring. For this reason, the documented outlines from the field observations where used to remove snow in the simulated snow cover distribution. This was done by assessing the depth of the most likely avalanche release, based on the minimum structural stability index. If water is present in the snow cover, the maximum local LWC is used, when this exceeds 2%. However, all results shown here are for dry snow avalanches. After determining the most likely fracture depth, snow above this depth was removed on the date and time the avalanche reportedly occurred (see Fig. 3).

3. RESULTS

We present results here for the 2016-2017 winter season. Fig. 4 shows the peak of season snow depth distribution. As can be seen, the snow depth is lower in the valleys. First, the precipitation in mountainous areas typically increase with elevation. Second, snow melt occurs earlier in the year in the lower valleys. Also, the dominating winds from westerly directions mainly deposit snow in the east facing

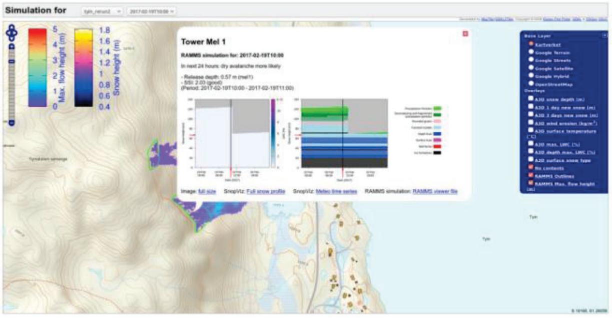

Fig. 3: Interactive web page showing how the information is presented to the forecasters. The model variable of interest can be selected. Shown now is the predicted maximum flow height of the avalanche. The pop-up shows details of the predicted avalanche. In this case, the model predicted a fracture depth of 57 cm. Due to the presence of a documented avalanche outline in the database, the model removed snow above the fracture depth in the further calculations.

slopes, where the avalanche control towers are located. Qualitatively, the model describes the known distribution patterns of snow well.

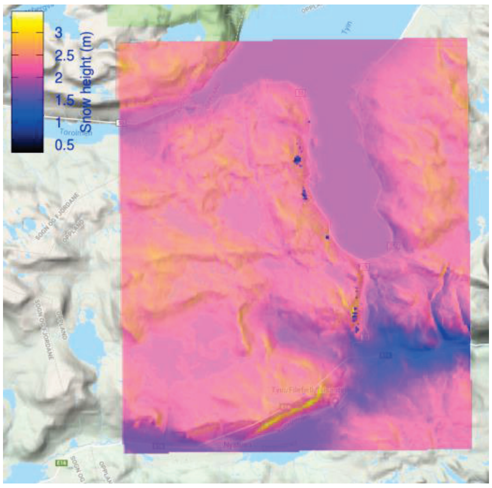

Fig. 4: Snow depth as simulated by the model on19 May 2017.

Figure 5 shows the reported fracture depth versus the simulated one. It is clear that a correlation is absent. The used stability index to determine the fracture depth is the structural stability index (SSI). Other stability indices did also not show a significant correlation. We attribute the poor agreement to both modeling errors, as well as difficulties of correctly identifying release depths visually from a large distance.

Ultimately, however, the more interesting output from the model chain is the runout distance from the avalanche. This value determines whether or not the road is at risk of being hit by the avalanche. As the local observer documented polygons, it is possible to derive a runout distance by following the flowlines from the release area and searching at which distance these flowlines cross the documented polygon. A similar procedure can be done for the RAMMS simulations.

Figure 6 shows the runout distance derived using the documented polygon versus the observed one. Here, a significant correlation is present. It further suggests that the mismatch between observed and simulated release depth is probably caused by combined uncertainties in both the estimated one by the local observer as by the model chain.

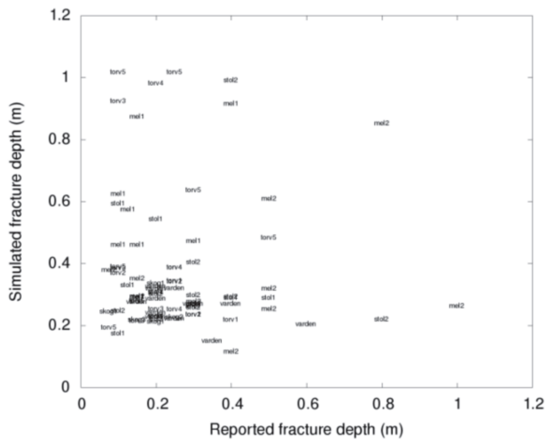

Fig. 5: Reported vs simulated fracture depth, for all the reported avalanches. The labels denote the names of the specific avalanche control tower.

4. DISCUSSION

The results obtained after two years of operational use are encouraging. We stress, however, that a pre-operational testing and calibration phase is required. This phase is ideally performed using data from “representative” winters.

The Alpine3D model with the Winstral algorithm was qualitatively able to represent snow depth patterns, with snow accumulating in lee slopes, thus also below the avalanche control towers. The local observer reports an overestimation of the snow depths, although a quantitative estimate of the overestimation is difficult to get. Given the simulated snowpack state, the RAMMS model was able to reproduce the observed avalanches, although modifications of the initial settings for the model may achieve better results.

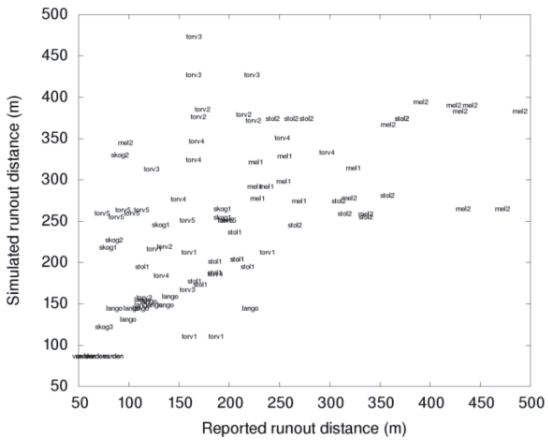

Fig. 6: Reported vs simulated runout distance, for all the reported avalanches. The labels denote the names of the specific avalanche control tower.

Furthermore, it was found that the correlation between reported fracture depths and simulated ones is poor, whereas the more important runout distance does show a positive correlation. This indicates that the model chain is able to provide information about the runout distance of potential avalanches, which is the important variable to assess the risks for the road. However, we found that the one release scenario that was calculated by RAMMS-Extended needs to be extended by an uncertainty estimate. Future work will focus on assessing multiple release scenarios based on the simulated snowpack conditions, to provide an uncertainty estimate from the ensemble of simulated avalanches.

5. CONCLUSIONS

A chain of automatic weather stations coupled with numerical models has been used in an “operational mode” to assess the current avalanche danger in a specific, local environment. The model chain was able to provide accurate runout distance calculations and predict fracture depths using the modelled current snow conditions. The system has demonstrated that with certain prerequisites it is possible to assess the current avalanche danger in a local region.

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