COUPLING OPERATIONAL SNOWCOVER SIMULATIONS WITH AVALANCHE DYNAMICS CALCULATIONS TO ASSESS AVALANCHE DANGER IN HIGH ALTITUDE MINING OPERATIONS

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ABSTRACT: The Codelco Andina copper mine is operating in high alpine terrain where avalanches pose a threat to the operations and the infrastructure. A dedicated avalanche warning service is responsible for opening and closing the heavily used access road. To support their decision making process, a system is developed 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. This model is run within the spatially explicit Alpine3D tool, taking into account the radiation budget in complex terrain. The SNOWPACK model provides snowpack stability estimates and, based on the weak layer depth, potential fracture depths and snowpack properties of the slab. For example, for wet snow avalanches, which is the major threat in the mine, the simulations indicate if water is accumulating at layer boundaries inside the snowpack. The model accumulation depth defines the potential fracture height. This information is displayed on maps, but is also directly used to provide the initial conditions for the avalanche dynamics model RAMMS for predetermined avalanche paths. The properties of the entrained snow, which we show is also an important factor to determine avalanche runout, are also provided by the Alpine3D simulations. 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 aid the avalanche risk assessment

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

1. INTRODUCTION

Mining activities are often located in high mountain terrain where snow avalanches can disrupt operations by blocking important transportation routes and access roads. Mine operations can be severely affected by the road closures. Since severe financial losses result because of road closures, the mine aims to minimize closure times with a “tolerable” risk. Often the opening-closing decisions are taken based on unreliable, scarce, and haphazard pieces of information.

In this work we use avalanche dynamics simulations on selected avalanche paths in order to assess avalanche risk. The novelty in this approach is that the avalanche dynamic model (RAMMS, see Christen, 2010 and Vera, 2015) is driven by modeled snowcover conditions and not by calibrated input parameters chosen by an avalanche expert. Initial and boundary conditions, such as release heights and entrainment layers, are calculated from snowcover simulations. The goal is to test the application of a model chain which can assess the current avalanche run out distance and inundation area in a local region using current meteorological data.

During the last five winter seasons, the WSL Snow and Avalanche Research Institute SLF together with the Codelco Andina copper mine (Chile) have developed an avalanche risk assessment tool that consists of a chain of modelling systems that include automatic weather stations, the snowcover models SNOWPACK and Alpine3D and avalanche dynamics model RAMMS. The model chain uses the measured meteorological data from a network of automatic weather stations. The current snow and meterological data is used to force point snowcover simulations with SNOWPACK (See Bartelt 2002, and Lehning, 2002) run within the spatially explicit Alpine3D, (Lehning, 2006). Once the snowcover conditions are modeled, the model chain writes the initial and boundary conditions for the avalanche dynamics model on 20 selected avalanche paths which typically endanger the road operation.

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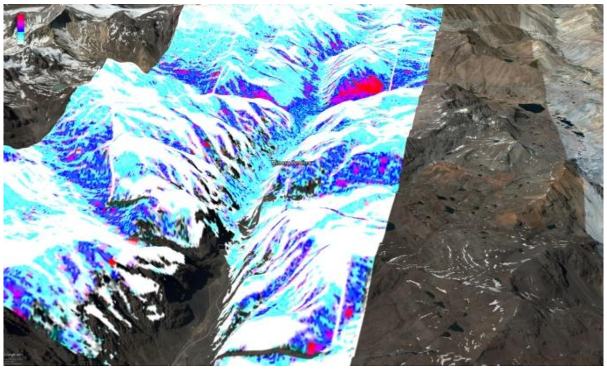

Fig.1. Example of a liquid water content calculation performed with Alpine3D projected on a 3D image from the valley. White areas indicate dry snow, colors indicate wet snow, where the color shows the maximum liquid water content somewhere in the snowpack.

The outputs of the model chain can be divided into two results: (a) the snowcover modeling provides the winter operation team with a detailed information regarding snowcover stratigraphy, snow density, snow temperature and liquid water content along the entire valley. This information is very valuable in itself to assess the avalanche situation along the road (see Fig.1) The second result (b) the model chains delivers a set of avalanche simulations with the runouts and inundation areas expected in each selected avalanche path given the current snow conditions (see Fig.2).

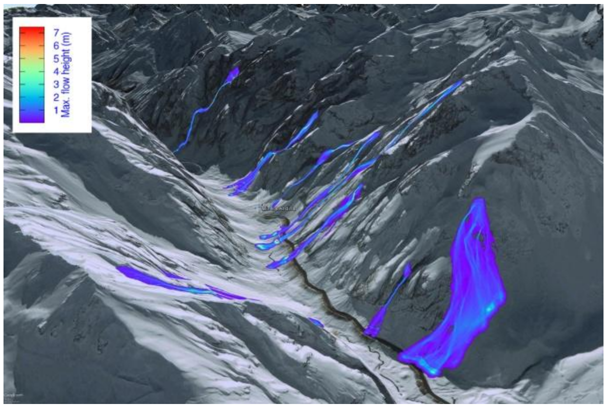

Fig.2 3D Image of the dynamic hazard map obtained in one calculation step from the model chain.

2. MODEL CHAIN, INITIAL AND BOUNDARY CONDITIONS

The Codelco Andina mine operates a network of automatic weather stations situated at the valley bottom at 2770 m.a.s.l., east facing at 3550 m.a.s.l., west facing at 3720 m.a.s.l and south facing at 4200 m.a.s.l. The stations deliver air temperature, atmospheric pressure, relative humidity, incoming and reflected shortwave radiation, snow height, snow surface temperature and wind measurements. The meteorological and snow information is used to drive the snowcover models SNOWPACK (See Bartelt 2002 and Lehning, 2002) distributed spatially through Alpine3D (see Lehning, 2006), see Fig.1. SNOWPACK results have been tested along the valley road by direct comparisons with traditional snow pits during the last five winter seasons, see Vera (2016).

Once the snowcover conditions along the road are known the input conditions for the avalanche dynamics model RAMMS (See Christen, 2010) are written. The initial and boundary conditions for RAMMS extended simulations include fracture depth, average snow density, temperature and liquid water content in both the avalanche release and entrainment zones (see Vera, 2015 and Vera, 2016).

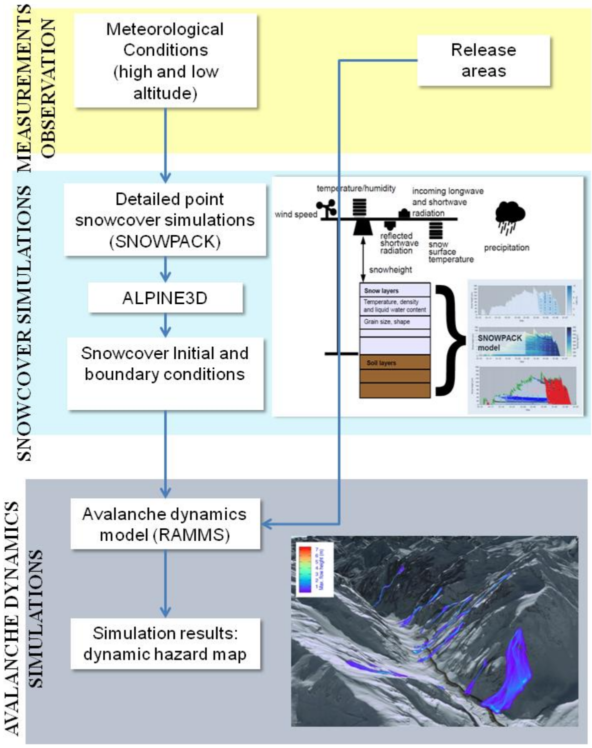

Fig 3. The model chain: automatic weather stations provide input into the snowcover models which in turn define the initial and boundary conditions of the avalanche dynamics simulations.

The task is not trivial and requires both first hand knowledge of the local terrain and hands-on experience with the avalanche model RAMMS extended.

Historically the ‘Cajon del rio Blanco Valley’ has two main avalanche cycles: dry avalanche activity during snow storms and wet avalanche cycle during the warm periods after new snow. This pattern can occur several times in a single winter season. In case of dry snow the system uses the new snow along the avalanche path for both the fracture and erosion depths in the avalanche dynamics calculations. This criteria is based on 40 year experience of the operations team. The steepness of the avalanche paths (together with the complete absence of human activity on the slopes) makes spontaneous avalanches the most frequent case for dry snow avalanches.

In the case of wet snow avalanche we use the depth of the maximum water ponding at layer interfaces as described in Wever, 2016 and Vera, 2016. The snowcover simulations indicate that water accumulates at microstructural layer transitions inside the snowpack (see Fig.1). The depth at which this occurs is used to define the potential fracture depth. This method has been used for the last four winters providing satisfactory results for both avalanche occurrence prediction and avalanche size estimation (see Wever, 2016).

These two criteria provide us the fracture depth and the erosion depth along the avalanche path for both dry and wet cases. The slab properties are defined by the average snow density, temperature and water content which extends from the maximum water accumulation point up to the snow cover surface. Average densities and temperature are used in the case of dry snow. These are obtained from the Alpine3D simulations at the point where the slab releases.

The second input necessary to perform the avalanche dynamics simulations is the release area. The typical avalanche path in the ‘Cajón del rio Blanco’ valley are steep gullies with define starting areas, which make this task tractable. For every avalanche path three different release areas are defined. Those releases are chosen from the experience and mine records from the last 40 years for each avalanche path. The final scenario chosen for each case is defined using three classes “small”, “medium” and “big”. The definition of each class is defined by historical records and experience.

Finally, to perform an extended RAMMS simulation, several flow parameters must be defined. These parameters depend on the avalanche path steepness, roughness and torsion. However, once enough experience for each avalanche path is accumulated, these parameters are known and do not vary with different snow conditions (see Vera 2016).

3. RESULTS

The outputs from the model chain are twofold: (a) the snowcover information obtained from the Alpine3D simulations in the whole valley (See Fig. 1). These simulations calculate the snow stratigraphy, snow temperature, density and snow water content in the study area. This information itself is valuable since the operation crew obtains an accurate description of the current snowcover situation for the whole valley. This information is used mainly by the winter operation team to estimate the probability of avalanche occurrence

(b) Secondly, the model chain automatically initiates 20 avalanche simulations in the selected avalanche paths (see Fig. 2). The calculations can be visualized in 3D images via Google Earth or in a regular 2D projection plotting maximum flow height or avalanche height.

These results (a) and (b) combine to create a so-called ‘dynamic avalanche hazard map’. The model chain recalculates every time a new meteorological measurement is available.

In the following section we show two different real case studies where the model performed accurately with two different snow conditions: (a) Wet snow after a long dry warm period Figs. 4 and 5 and (b) dry snow after a storm Figs 7, 8 and 9.

3.1 *Comparison real case avalanches with output simulations: wet case avalanche MO-4 15-10-2013*

The first case study occurred on the 15th of October 2013 on the avalanche path denoted MO-4. The MO-4 releases on a steep bowl at 3700 m.a.s.l. and is channelized into a steep gully (see Fig.4). The MO-4 avalanche released as a wet snow avalanche after a warm period without precipitation and any avalanche activity in the previous 32 days. The Alpine3D simulation calculated water percolating deep in the snowcover, see Fig.6. The calculation shows the high water ponding occurred particularly on the 15th of October exactly when the avalanche released. This result was used to calculate the average slab properties in the input values for the RAMMS simulation (as done in Vera, 2016). The simulation matches the observed run out distance, inundation area and the avalanche deposits patterns. The model chain was likewise able to reproduce the main features observed from the real avalanche, see Figs. 4 and 5

Fig.4. Avalanche path MO-4 released as wet avalanche after 32 days of stable weather and no avalanche activity damaging mining machinery

3.2 *Comparison real case avalanches with output simulations: dry case storm 08-08-2015*

The second case study concerns the two days snow storm occurred between the 7th and the 8th of August 2015. During these two days, more than 2 meters of new snow fell accompanied by north westerly winds. Those storms are typical in the central Andes where this pattern can occur several times per winter season. In this case, 16 avalanches were recorded hitting the road. All of them reached size 3-4 in the Canadian avalanche size scale. The winter operation team could operate a drone along a section of the road obtaining an accurate estimation of the run out distances and area covered by the avalanche deposits in this part of the road after the storm. Between the km 21 and km 25 of the road the drone recorded four avalanche events (see Fig.7). Three of them were simulated during the storm as part of the model output. The run out distances and area covered by deposits measured with the drone matched obtained with the ones obtained with the model chain see Figs. 7, 8 and 9.

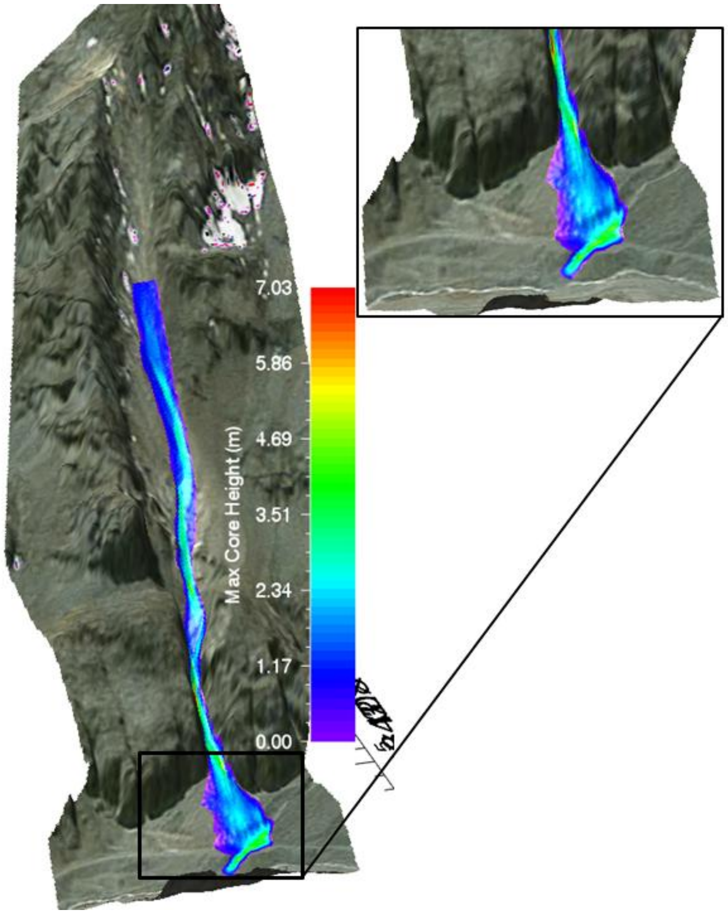

Fig. 5 Avalanche runout calculation performed by the model for the MO-4 avalanche path. Inset depicts the calculated deposition field of the avalanche. Note the location of the avalanche arm is well represented

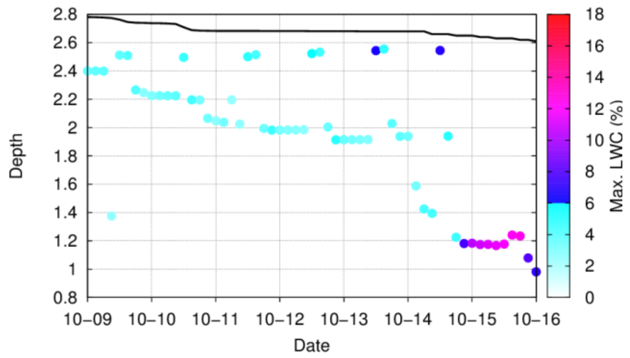

Fig.6. Snow height (black solid line) and depth of maximum liquid water content, colored by the volumetric liquid water content at this depth (%) in the release area of the MO-4 avalanche, as calculated by Alpine3D. The avalanche occurred on October 15.

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 mine is presently using the system as a reliable source of information which is directly tied into operational decision making process. The first two layers of the system, automatic weather stations and numerical snowpack modelling, are used to gather information about the current avalanche risk situation. The runout calculations also provide the decision makers with qualitative information concerning the extremity of avalanche runout.

However, several research gaps remain and speciall situations can occur where the system must be improved and tested. The operation in the ‘Cajon del rio blanco valley’ has an special topography and terrain characteristics that constrain the snowcover evolution and avalanche flow regime. Firstly the model chain has been tested in a valley where:

- The avalanche paths are mostly confined gullies with clearly defined release areas and runouts.
- The system is used at a local scale with uniform meteorological conditions. Warming periods with well-known wind patterns between storms are also similar.
- Accurate digital elevation model (DEM) and meteorological measurements are available for the entire valley.

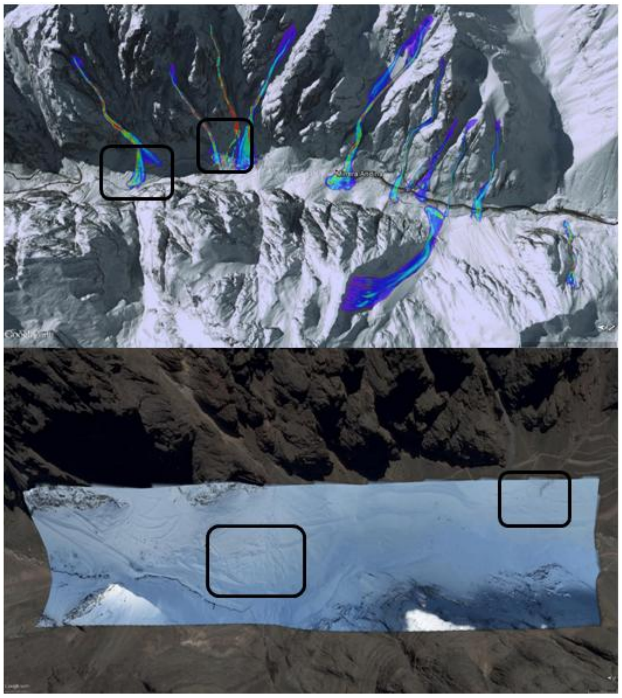

Fig.7 Comparison of the output delivered by the model chain and an aerial photography performed by a drone one day after the storm. Close up from the avalanches in Figures 8 and 9.

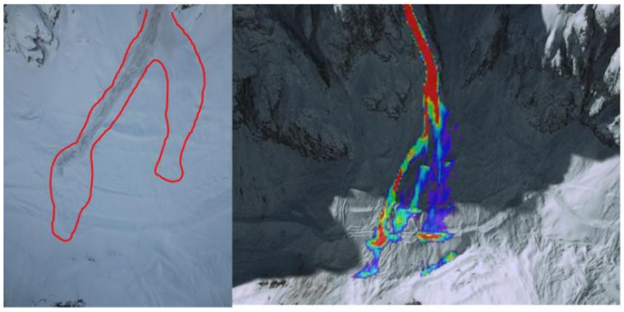

Fig.8. Avalanche runout photography and avalanche simulation calculated for that day with the system.

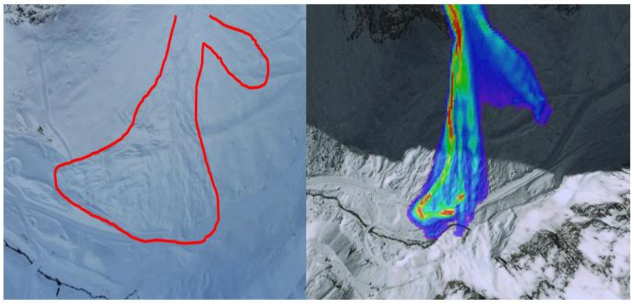

Fig.9. Avalanche runout photography and avalanche simulation calculated for that day with the system

- No human triggering. In the entire mine working area, recreational activities are strictly forbidden and no work is performed outside the mining zones.

The system was additionally tested and calibrated using four years of both meteorological and event experience. Mine records, however, document 40 years of road operation. With this information it is possible to calibrate the avalanche dynamics model which depends on the snow conditions and the avalanche paths (see Vera, 2016).

The tool is used on a regular basis by the winter operation crew and is now one piece of the daily information used to make decisions on how the industrial road is to be operated.

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 run out distance calculations and area covered by deposits using the modelled current snow conditions. The system has demonstrated that with certain prerequisites it is possible to assess the current avalanche risk in a local region. However, research gaps remain, such as the automatic specification of release areas and selection of erosion depths. The initial results are encouraging, but will always require calibration and experience of local experts.

6. REFERENCES

Bartelt, P. & Lehning, M.
A physical SNOWPACK model for the Swiss avalanche warning Part I: Numerical model
Cold Reg. Sci. Technol., **2002***, 35*, 123-145

Christen, M.; Kowalski, J. & Bartelt, P.
RAMMS: Numerical simulation of dense snow avalanches in three-dimensional terrain. X, doi:10.1016/j.coldregions.2010.04.005.
Cold Reg. Sci. Technol., 2010, 63, 1-14

Lehning, M.; Bartelt, P.; Brown, B. & Fierz, C.
A physical SNOWPACK model for the Swiss avalanche warning Part III: Meteorological forcing, thin layer formation and evaluation
Cold Reg. Sci. Technol., **2002**b*, 35*, 169-184

Lehning, M.; Völksch, I.; Gustafsson, D.; Nguyen, T. A.; Stähli, M. & Zappa, M.
ALPINE3D: a detailed model of mountain surface processes and its application to snow hydrology
Hydrol. Proc., John Wiley & Sons, Ltd., **2006***, 20*, 2111-2128

Schweizer, J.; Bellaire, S.; Fierz, C; Lehning, M & Pielmeier, C. Evaluating and improving the stability predictions of the snow cover model SNOWPACK .
Cold Reg. Sci. Technol., 2006, 46, 52-59

Vera Valero, C.; Jones, Y. B. W. & Bartelt, P.
Release Temperature, Snowcover Entrainment and the Thermal Flow Regime of Snow Avalanches
Journal of Glaciology, **2015***, 61(225)*, 173-184

Vera Valero, C.; Wever, N.; Bühler, Y.; Stoffel, L.; Margreth, S. & Bartelt, P.
Modelling wet snow avalanche runout to assess road safety at a high-altitude mine in the central Andes
Natural Hazards and Earth System Sciences Discussions, **2016***, 2016*, 1-41

Wever, N.; Fierz, C.; Mitterer, C.; Hirashima, H. & Lehning, M.
Solving Richards Equation for snow improves snowpack meltwater runoff estimations in detailed multi-layer snowpack model
Cryosphere, **2014***, 8*, 257-274

Wever, N.; Vera Valero, C. & Fierz, C.
Assessing wet snow avalanche activity using detailed physics based snowpack simulations
Geophysical Research Letters, **2016***, 43*, 5732–5740