Analysis of one avalanche zone in the Eastern Pyrenees (Val d'Aran) using historical analysis, snow-climate data and mixed flowing/powder avalanche modelling.

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ABSTRACT: Over the last 30 years, Andorra and northern Catalonia (Pyrenean regions) have frequently been affected by avalanche events having as result more than 11 deaths in Andorra and 40 deaths in Catalonia. Some of these events affected buildings and infrastructure producing multi-million Euros losses. As a consequence, the governments of Andorra and Catalonia have increased their efforts to mitigate the danger and risks associated with avalanche hazard, particularly in urban and ski resort areas; for this reason it is important to have a realistic hazard maps, obtained with an engineering methodology based on historical data, snow-climate analysis and avalanche dynamics simulations. The simulations account for different flow regimes induced by the snow and weather analysis (snow height, snow temperature, spatial distribution and moisture content). The application of thermomechanical avalanche dynamics models consequently underscores the importance of gathering historical data including precipitation records, snow cover data avalanche flow behaviour, including the predominant avalanche flow regime.

KEYWORDS: Avalanche dynamics, avalanche modelling, snow climate, Eastern Pyrenees.

1. INTRODUCTION

The purpose of this paper is to demonstrate how historical analysis, snow-climate data and avalanche dynamics models can be combined to reconstruct a specific avalanche event. Central to this study is the ability of avalanche dynamics models to account for snow entrainment and study of different avalanche flow regimes, such as powder or wet flows. In regions like the Eastern Pyrenees such analyses are necessary to help assess the overall danger of potential, catalogued and registered avalanches. The study of historical extreme events with a high level of danger interacting with vulnerable infrastructure is required to qualitatively and quantitatively study avalanche danger in terms of intensity, volume, and area of involvement.

The proposed analysis is initially based on the statistical treatment of the snow-climate and the geomorphological data of the slopes by means of digital terrain models (both, of the slopes as well as of the vulnerable areas) created from altimetric detail cartography (LIDAR).

Parallel to and prior to the application of numerical models, all historical data available in the area must be analysed. These include aerial images, historical photographs of the area, surveys of the population, popular stories, news in the media, topographic and cadastral information.

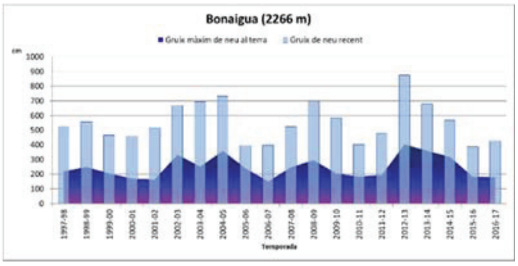

Figure 1: Evolution of the maximum annual snow depth on the ground and recent snow of the *Bonaigua* weather station (2266 m).

These background data is necessary to know which method of calculation and which numerical models are the most appropriate in order to reproduce the maximum recorded events according to snow conditions at the time. We will also be able to calibrate the different numerical models and analyse the most numerically sensitive parameters.

2. STUDY AREA AND PREVIOUS DATA

The main projected study area (*Comalada-Baqueira*) is located in the Aran Valley, the only area in the Pyrenees of Catalonia with an oceanic climate. The main feature is the frequent affectation by air masses of Atlantic origin, resulting in mod-

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erate snowfalls and with a certain persistent nature due to the effect of orographic retention of flows from North and Northwest. An important element for the avalanche activity is the fact that the rain-snow level changes are common and pronounced, as the warm and cold fronts frequently alternate. This causes snowy situations with dry and cold snow followed by rains reaching relatively high altitudes. These conditions favour the activity of avalanches of wet snow.

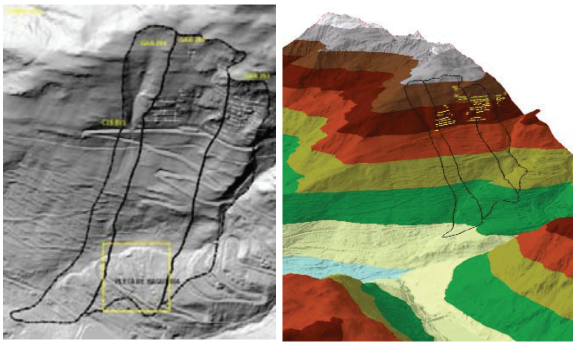

Figure 2: Digital elevation model (LIDAR) with a mesh of 2m x 2m. Outline of the 2003 avalanche event.

Figure 3: General map of the study area.

The analysed avalanche zone is *Comalada* (code GAR203 from the BDAC, Avalanche Data-base of Catalonia, ICGC). The identified avalanche zone has release areas at very variable levels, ranging from maximum and minimum of 2080-1640 meters, mostly between 1800 and 1900 meters. The general morphology corresponds to open slopes with discontinuities constituted by ravines; convexities alternate with concavities constituting a typically convoluted terrain. The average gradients of the starting zones range from 24° to 37°.The orientation is essentially sunny, between S and SSW. Regarding the wind's action, there is snow over-accumulation with winds from the W, NW, N and NE. The wind-drifted snow is both on the leeward side of the peak ridges (basically with NW, N and NE winds), as well as cross or lateral overaccumulation with winds of the W due to the convexities and bumps which stands out the slopes of the starting zones and the avalanches paths. Obviously, there are erosions in the raised points such as bumps and other topographical configurations.

The main data and processes that we have used to discuss the suitability of the numerical models, and to do a retro-analytical calibration, are the following:

- Search and statistical analysis of snow and weather series for the last 33 years.
- Photographs of the event of the year 2003.
- Testimonial and cadastral information of the 2003 event.
- Snowpack conditions of the day of the event.

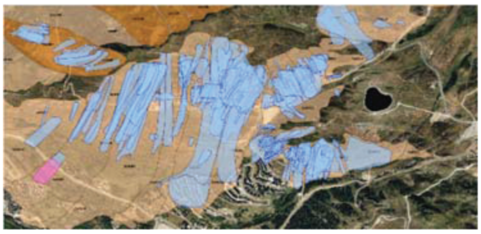

Figure 4: Cadastral inventory map of avalanche phenomena observed in the last 20 years.

Figure 5: Structural damage to the front line of buildings in the avalanche area GAR203, January 31, 2003. Source: Avalanche Forecasting Survey of Aran.

It is interesting to highlight that the avalanche of 2003 is associated with a T = 100 years in relation to its range, but with a thickness of snow release associated to T = 20-30 years.

3. NUMERICAL MODELS.

3.1 Ramms dense flow

Once all the characteristics that define the slope under study are described, it is proposed to perform a first numerical model in dense snow by means of numerical modelling. In our particular case we begin by applying the operational **RAMMS** model (Rapid Mass Movement) developed by the WSL/SLF of Switzerland. The **RAMMS** calculation module was developed to perform simulations on avalanche propagation in mountainous areas and has now become a widely used tool in Switzerland for the determination of avalanche hazard. The nucleus of the program is a second order numerical solution, which allows us to calculate the velocities and heights of the snow flow over three-dimensional digital terrain models (Christen et al., 2008).

The operational RAMMS model considers only dense avalanche flows. The model is still based on the Voellmy equations (1955), widely used in snow engineering in Switzerland. It is assumed that cohesion stresses in the body are small, and that the resistance to the flow is concentrated at the base (Bartelt et al., 1999). Voellmy proposed an equation for the shear stress at the base consisting of two terms, a Coulomb-friction term (parameter μ)and a turbulent term (parameter ξ)proportional to the velocity squared:

$$S = \mu N + \frac{\rho g U^2}{\xi}$$

Where ρ is the density of fluid; g is the gravitational constant; $N$is the slope-perpendicular normal force and $U$the depth averaged velocity of the avalanche. The friction parameters change as a function of avalanche return period and avalanche type (dry, wet). From the results obtained in the two-dimensional analysis for the thickness of snow and release polygons established based on the information of the event of 2003, the flow does not affect the area of the *Pleta de Baqueria* where there were structural defects in the buildings adjacent to the slope.

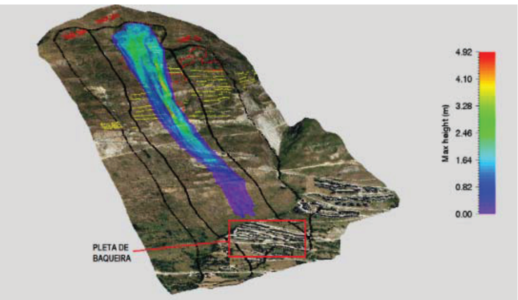

Figure 6: Snow height results of the operational **RAMMS** model.

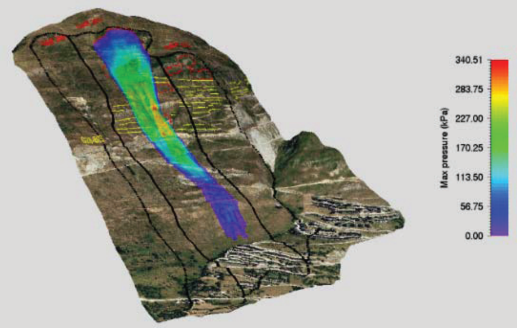

Figure 7: Dynamic pressure results of the operational **RAMMS** model.

3.2 Aval 1d powder avalanche

Topographically, the avalanche zone corresponds to a very heterogeneous sector with convex and grooved reliefs, which is not suitable for being modelled with a one-dimensional model such as **AVAL 1D (Christen et al., 2002)**, given the irregularity of the various flow profiles, both in longitudinal profiles as well as to the width of the sections. However, a profile in the area of maximum snow accumulation and propagation is carried out according to the result of the bidimensional analysis in dense snow **RAMMS**.

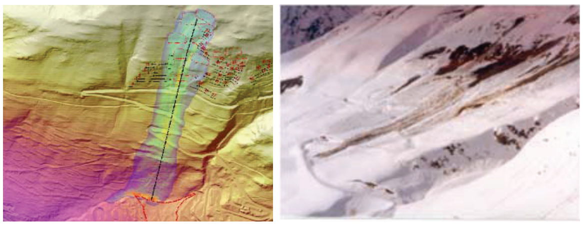

Figure 8: Most unfavourable longitudinal profile of the slope.

A dynamic pressure in the range of the 2-3 kPa is obtained on the area of the first line of buildings due to the powder effect.

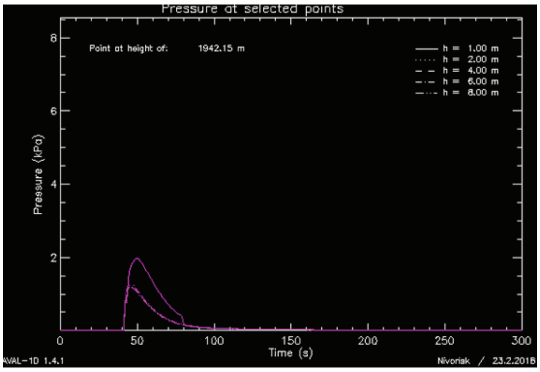

Figure 9: Dynamic pressure result **AVAL-1D** model.

Despite the certain consistency of the result based on the stipulated climatic parameters (density, suspension rate, erodibility, d_0), we still have the problem to reproduce the entire influence surface perimeter in order to carry out the respective hazard map.

3.3 Mixed flowing/powder avalanche modelling.

In view of the comparison between the standard **RAMMS** model results and the available historical data, we decided to apply the extended **RAMMS** model to simulate the event as a mixed flowing/powder avalanche (Bartelt et al., 2016). The model is presently being tested on a wide range of case studies with different snow and weather conditions, including wind drift calculations which allow engineers to calibrate the model to the point of being able to obtain and understand the role of different snowcover conditions on avalanche runout (Stoffel et al., 2018). It is therefore ideal to study the avalanche that took place in 2003.

The extended **RAMMS** model calculates both the motion of the avalanche core, as well as the motion of the powder cloud. During the cloud formation phase, the motion of the core and cloud are strongly coupled. The core imparts initial mass and momentum to the cloud. However, after formation, the motion of the core and cloud are treated as independent flows. The core is strongly influenced by terrain, while the cloud is essentially independent, travelling in the direction supplied by the core, and often past the core, which can stop or be deflected by terrain features.

Another important feature of the extended model is the treatment of snow entrainment (see Bartelt et al., 2018). The extended RAMMS model accounts for both the temperature and erodibility of the snowcover. The intake of cold snow serves to increase the fluidization of the avalanche core and therefore formation of powder clouds. The formation of destructive powder cloud can form only under certain terrain, temperature and snow conditions.

The simulation parameters, including snow temperature, we use are based on the previously described historical data:

► INITIAL THICKNESS

We simulated the avalanche considering, in one case, the total amount of fresh snow in 72 h (HN72h=165 cm) applying a settlement ratio, and in a second case, the difference in the snowpack depth between third and first day (HS3dd=108 cm). In both cases wind-drifted snow accumulation is added, as result of the knowledge of the local behaviour of the wind due to the analysis of a nearby *FlowCapt* sensor. To calculate the possible snow cover erosion rate. We considered two snow cover scenarios:

● Option 1) Two layers of snow (total 60 cm): up, 20 cm of 140 kg/m3 at -10°C+ below, 40 cm of 180 kg/m^3 at -6°C.

● Option 2) One layer of snow: 72 cm of 120 kg/m^3 at -10°C.

4. RESULTS AND DISCUSSION: FINAL MODEL MIXED FLOWING/POWDER AVALANCHE

4.1 Dynamic pressure of the dense avalanche

Fig. 10 depicts the central zone of the mixed avalanche, relative to the behaviour of the granular flow (dense), we have pressures in the range of 30 kPa, just in the ravine line (change of gradients) and first line of adjacent houses. The model results correspond with those observed in the 2003 event. In this simulation (unlike previously performed exclusively with the operational **RAMMS** model) a slight influx of the flow in the *Pleta de Baqueira* area is observed.

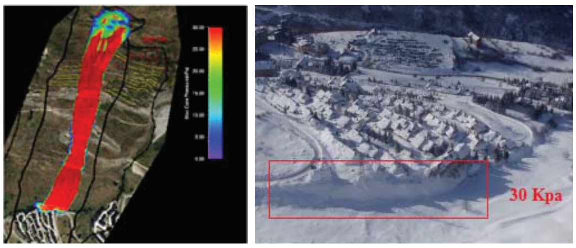

Figure 10: Impact pressure avalanche core (extended **RAMMS** model).

4.2 Dynamic pressure of the powder avalanche

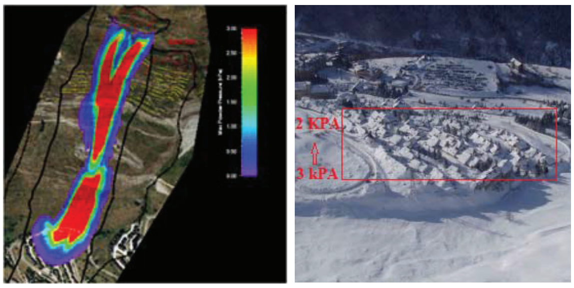

Figure 11: Impact pressure powder cloud (extended **RAMMS** model).

Fig. 11 depicts the dynamic impact pressures derived from the powder effect. At the point where the flow finds the sudden change of the terrain, the gap of the ravine, and the first line of houses, we have pressures associated with the powder in the range of the 3 kPa. This pressure decreases as the powder cloud spreads and moves away from the point of impact in the ravine area. We see how the flow affects an important part of the *Pleta de Baqueira* reproducing the 2003 event with fairly precise accuracy.

4.3 Maximum height powder cloud.

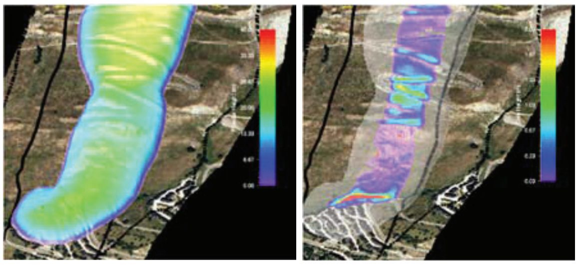

Figure 12: Height powder cloud result biphasic powder/dense flow **RAMMS** Extended model.

According to the mixed flowing/powder numerical model, the height that the powder that reached in

Pleta de Baqueira was around 25 meters. This result agrees with eyewitness accounts in the area, giving some validity to the simulation results.

4.4 Dynamic sequence of the mixed avalanche model of reference.

In the interpretation of the results obtained in this last experimental model we can affirm this type of mixed avalanche model is the one that is closer to the reality and to events observed in this area. Hence the importance of being able to perform this model (back-calibrated) with historical and snow-weather data.

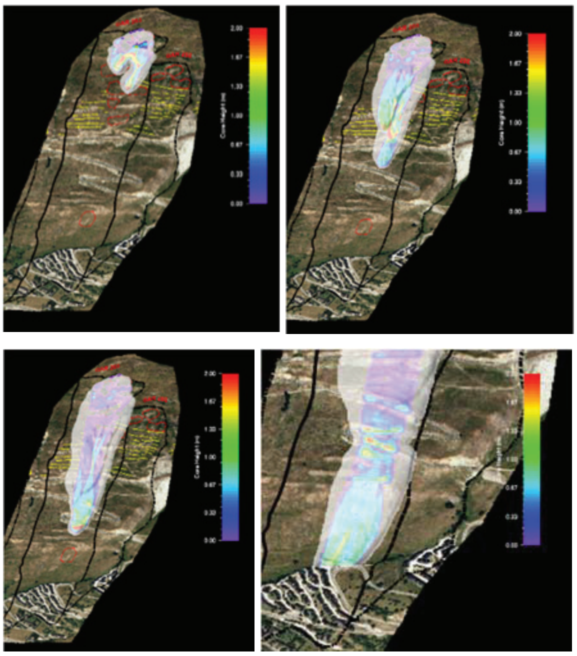

Figure 13: sequence of simulation results for the mixed flowing/powder model. White: cloud. Color: core height.

5. CONCLUSIONS

We can conclude that the current market of two-dimensional numerical models for dense avalanches (**RAMMS**) are useful to simulate avalanches associated with specific return periods. They have been calibrated to give us an overall idea about the maximum impacts in the runout zones. These models are often applied by modifying the thicknesses and areas of the release polygons, as well as occasionally the cohesion and the density of the snowpack (Christen et al., 2010).

However, our case study of a mixed flowing/powder avalanche, demonstrates how avalanche motion is often more complex than we imagine, combining powder and dense components in a single avalanche flow. This complexity results in the need to better understand the thermomechanical properties of the snow cover (temperature, erodibility, extent) can also influence the simulation results significantly. This explains why the fracture depth is an important parameter, but not the only parameter in numerical simulations.

It is necessary to think about the existing background/historical information such as: reliable snow and weather data, historical photographs, testimonies, cadastral maps, stratigraphic profiles and detailed digital elevation models. Only in this way it is possible to understand the physics that there is behind the numerical models and to be able to calibrate them in a coherent way to get the most reliable results. Post-modern avalanche engineering still requires careful examination and analysis of historical records. We must not be slaves to the numerical results, rather the expert must apply numerical methods such that they support critical and scientific analysis.

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