Towards a basic avalanche characterization based on the generated seismic signal

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ABSTRACT:
The primary reasons to study the seismic signal generated by avalanches are (1) to remotely detect snow avalanches and (2) to improve our understanding of avalanche dynamics. Geophones, coupled with other observation means, such as radar and videogrametric recordings, have provided increasingly detailed information on avalanche flow. For avalanche monitoring, on the other hand, one or perhaps several seismic sensors are placed in an avalanche track and are used to detect if and when an avalanche is released. While data of avalanche activity is of great interest, data on the size and type of the recorded avalanche events would represent very valuable additional information. In this study, we couple seismic monitoring with avalanche modeling to deduce avalanche characteristics from seismic signals. During the winter of 2012-2013, we monitored avalanche activity using time-lapse photography in combination with continuously recording seismic signals on a slope with well documented glide and wet snow avalanche activity above Davos, Switzerland. From 28 February to 13 March 2013, a relatively widespread wet snow avalanche cycle occurred and over 60 small to medium avalanches released on our study slope. The majority of these avalanches were recorded by our seismic sensor. Simple avalanche characteristics, including the size of the release area, the length of the path and the distance to the sensor, were derived from the time-lapse images. The data collected allowed us to simulate the observed avalanche events. We calculated the basal forces that generated the seismic signal. We then compared avalanche characteristics with the characteristics of the generated seismic signal, including signal length and amplitude and frequency distributions with time, with the aim of relating avalanche properties (volume, speed) with the measured signals.

KEYWORDS: seismic monitoring, avalanche activity, avalanche dynamics.

1 INTRODUCTION

Data on avalanche activity represent the most direct instability data for avalanche forecasting. Avalanche activity is generally estimated through visual observations, which are biased and imprecise, resulting in large uncertainties in the number and exact timing of avalanches. To improve avalanche forecasting, remote detection of snow avalanches is therefore required. Various studies have shown that seismic monitoring systems are very well suited for this task (e.g. Surinach et al., 2000; van Herwijnen et al., 2010).

While data of avalanche activity is of great interest for avalanche forecasting, a further improvement would consist of information on the size and type of the recorded avalanche events. In this study, we therefore aim at relating basic avalanche properties with the measured seismic signals by comparing avalanche characteristics with the characteristics of the generated seismic

signal, including signal duration and frequency characteristics.

2 METHODS

2.1 Instrumentation

During the winter of 2012-2013, we deployed a seismic monitoring system to remotely detect avalanches at the Dorfberg field site above Davos, Switzerland (Figure 1). The system consists of one vertical component geophone inserted in the ground, continuously recording seismic data at a sampling rate of 500
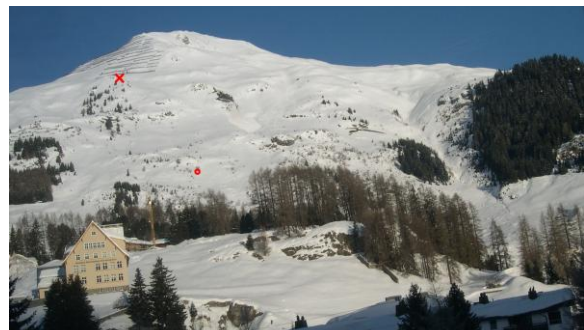

Figure 1: Overview of the Dorfberg field site above Davos, Switzerland. The location of the automatic weather station is marked with the cross and the location of the seismic monitoring system is marked with the circle.

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Figure 2: Left and middle: A wet-snow avalanche that released between 12:44 and 12:46 on 3 March 2013. Right: To derive basic avalanche characteristics, the contour of the release area (red area) and the avalanche track (green area) were mapped in a GIS. The location of the seismic monitoring station is marked with the yellow dot.

Hz. To store the data, a Single Board Computer (SBC) was mounted on a mast with solar power about 30 m from the sensor. Data were manually collected approximately every week. The Dorfberg site was also instrumented with an automatic weather station and continuously monitored with two automatic cameras recording images every two minutes from offices at the SLF to provide visual avalanche observations (van Herwijnen et al., 2013).

2.2 Data processing

Avalanches were identified on the images from the automatic cameras. We then derived simple avalanche characteristics, i.e. the size of the release area, the length of the path and the distance to the sensor, by mapping the contour of the avalanches estimated from the time-lapse images in a GIS (Figure 2).

To identify the seismic signal generated by the avalanches, we used the time of the avalanche occurrences determined from the images. Due to its proximity to the town of Davos, the Dorfberg field site is seismically very noisy. Nevertheless, since seismic signals generated by avalanches have distinct temporal and spectral characteristics (e.g. Suriñach et al., 2000; Rubin et al., 2012), we were able to identify avalanches in the seismic data by visual inspection of the waveform and the spectrogram, i.e. the evolution of the frequency content of the signal with time (Figure 3). The next step was to transform each signal into quantifiable features to compare the avalanches. We therefore extracted the total duration of the signal, the mean and maximum amplitude as well as features from the frequency domain.

2.3 Avalanche simulations

The data collected from the time-lapse images allowed us to simulate the observed ava-

lanche events using a numerical avalanche dynamics model (RAMMS; Christen et al., 2010). For the calculations we used the latest scientific version of RAMMS that considers entrainment and detrainment of snow along the avalanche flow path, cohesion and random kinetic energy (Bartelt and Buser, 2009; Buser and Bartelt, 2009; Bartelt et al., 2012). We simulated the avalanches using a Digital Elevation Model (DEM) with 2 m grid resolution. The snow height of the observed release areas and the height of
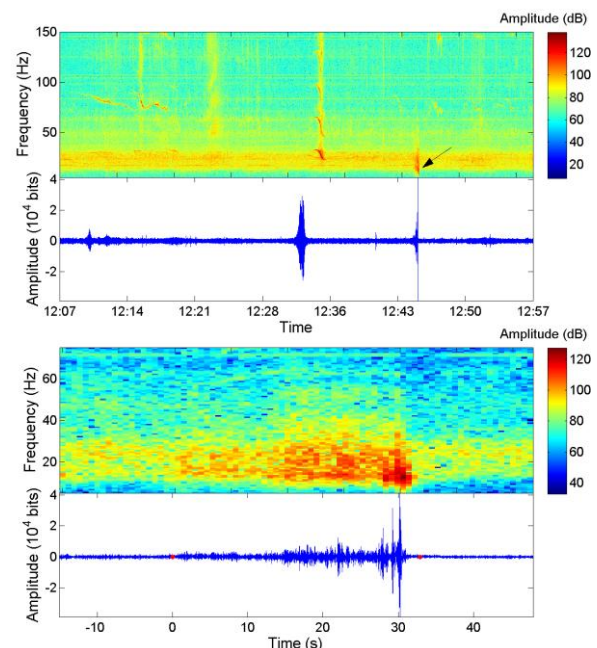

Figure 3: Top: Seismic data from 12:00 to 13:00 on 3 March 2013. The spectrogram (top panel) and the seismic signal (bottom panel) are shown. The arrow indicates the seismic signal generated by the avalanche shown in Figure 2. Bottom: Close-up of the spectrogram (top panel) and the waveform (bottom panel) of the avalanche. The red dots indicate the estimated start and end of the avalanche.

the erosion layer were based on snow height measurements of the Dorfgerg weather station. Initial input parameters were selected appropriate for wet-snow avalanches (μ = 0.3, ξ = 1000). Additionally, a snow temperature of 0 °C reflecting the isothermal snowpack and an initial cohesion value of 150 Pa were specified. We slightly adjusted the input parameters recursively to match the simulated avalanche to the observed flow path and runout distance and the duration of the seismic signal.

Simulation outputs include flow height, velocity, shear stress, flow volume, erosion and deposition volume, kinetic energy and momentum per time step (= 0.5 s).

3   RESULTS AND DISCUSSION

From 28 February to 13 March 2013, a relatively widespread wet-snow avalanche cycle occurred in the mountains around Davos. On the images from the automatic cameras, we identified 61 very small to medium wet-snow avalanches. Twenty-seven (41%) of these avalanches were positively identified in the seismic data. The remaining avalanches were either not detected by the seismic monitoring station, or ambiguous signals prevented us from positively identifying the avalanche in the seismic data. Conversely, 25 avalanches were clearly identified in the seismic data but not seen on the images from the automatic cameras.

3.1 Comparison of avalanche characteristics and seismic signal

The length of the avalanche estimated from the time-lapse images correlated well with the duration of the seismic signals generated by avalanches (top Figure 4). These results clearly show that signal duration t provides information on the length of the avalanche l.

According to the equation of motion with constant acceleration a and constant coulomb friction μ, the length of an avalanche is given by $l = \frac{1}{2}at^2$, with $a = g(\sin\theta - \mu\cos\theta)$. Here, g is the acceleration due to gravity and θ is the slope angle (the mean slope angle for the Dorfberg is 31°). Clearly, a constant acceleration and coefficient of friction for all avalanches is a gross oversimplification. Nevertheless, $l = 0.09t^2$ provides a good fit to the data ($R^2 = 0.90$; red line in top Figure 4), resulting in an estimate of the coefficient of friction of $\mu = 0.58$. While this value is plausible, it seems relatively high for wet-snow avalanches.

Seismic signals attenuate as the distance between the source and the receiver increases.
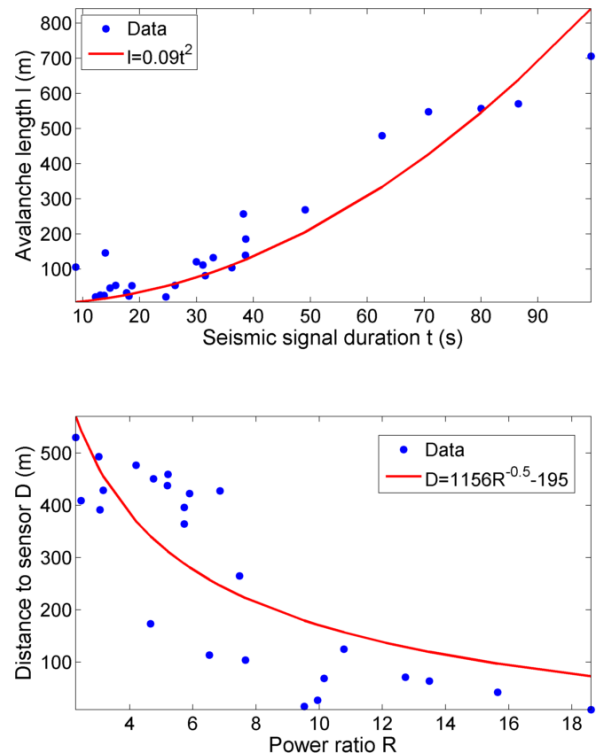

Figure 4: Top: Estimated avalanche length l with seismic signal duration t. The red line represents the best fit of l and t^2. Bottom: Distance D between the avalanche and the sensor with power ration R. The red line represents the best fit of D and $R^{-0.5}$.

Signal amplitude therefore decreases with distance and this attenuation is most pronounced in the high frequency range, resulting in a shift in the frequency spectrum towards lower frequencies. It therefore stands to reason that some basic information on the distance between the avalanche and the seismic sensor can be derived from the seismic signal.

Using signal amplitude to estimate distance is problematic since the size of the source events is not constant; a very small and very large event at equal distance from the sensor will generate very different signals. Luckily, the attenuation of seismic signals in the frequency range is less dependent on the size of the source event. Indeed, the power ratio $R = \frac{P_{15-60}}{P_{<15}}$, i.e. the ratio of the power in the frequency spectrum between 15 and 60 Hz and the power below 15 Hz (the natural frequency of the geophone is 14 Hz), decreases with distance D (bottom Figure 4). Thus, as the distance between the avalanche and the seismic sensor increases, more energy is shifted towards lower frequency signals, and a rough estimate of the distance can be obtained by $D = 1156R^{-0.5} - 195$ (red line in bottom Figure 4).
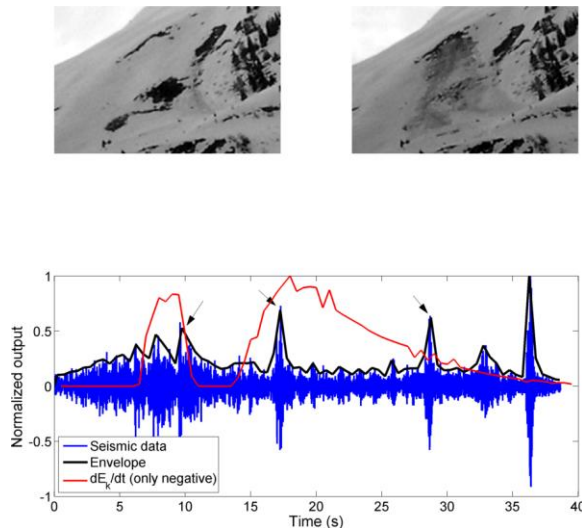
Figure 5: Top: avalanche that released on 11 March 2013 between 17:22 and 17:24. Bottom: Waveform (blue) and envelope of the seismic signal (black) with time. The red line represents the absolute value of the negative gradients of the kinetic energy E_k of the simulated avalanche. The arrows indicate the three events shown in Figure 6.

3.2 Comparison of numerical model results and seismic signal

The basic concept for linking the calculated model parameters and the seismic data is that in an avalanche, part of the kinetic energy E_k is transformed into seismic energy due to the interaction of the flowing mass with the ground (e.g. Suriñach et al., 2001). In an avalanche, seismic signals are generated when a moving snow particle decelerates due to interaction with the ground. As such, the generated seismic signal reflects the loss of avalanche power with time and should relate to decreases in instantaneous total kinetic energy.

Indeed, for an avalanche observed on 11 March 2013 at 17:22, the envelope of the seismic signal (i.e. the sum of the amplitude squared per simulation time step) and the absolute value of the negative gradient in E_k (positive gradients are set to 0) were fairly similar (Figure 5). During the first half of the avalanche, increases in the seismic signal at 10 and 16 seconds correspond to large (negative) gradients in E_k, as the avalanche passes over local terrain features and is forced to slow down and deposit mass (top of Figure 6). An increase in the seismic signal at 27 seconds also coincides with the simulated avalanche reaching a prominent terrain feature in the runout area (bottom left of Figure 6). However, overall, for the second half of the avalanche, the agreement between the negative gradient in E_k and the seismic signal was much poorer. This is likely due to the interaction of the
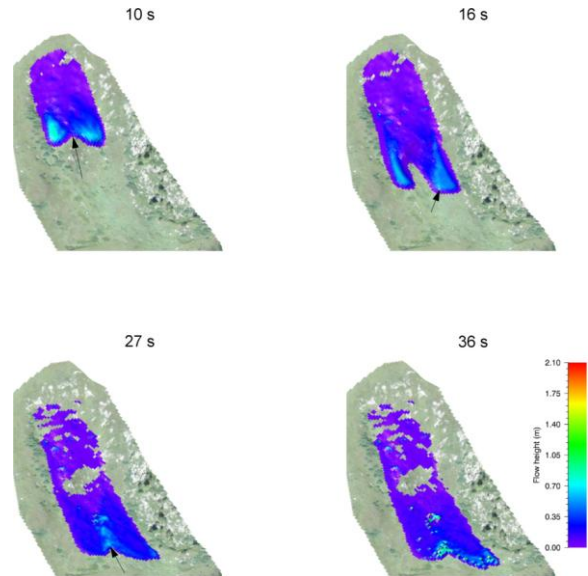
Figure 6: Flow height of the simulated avalanche shown in Figure 5 at four different times. The arrows indicate terrain features which slow the avalanche down and create noticeable seismic signals.

avalanche with the deposit of previous avalanches (which are not included in the model), and complex progressive and multiple failures of snow blocks during the deposition phase which cannot be modelled.

4 CONCLUSIONS AND OUTLOOK

Using avalanche occurrence data derived from time-lapse images, we derived simple avalanche characteristics and compared those to features of seismic signals generated by the avalanches. Our results show that seismic signal duration is closely linked to the length of the avalanche. Thus, signal duration provides direct information on the size of the avalanche event. Furthermore, we showed that a rough estimate of the distance between the avalanche and the seismic sensor can be obtained from frequency content of the signal, specifically, the ratio of the power in the frequency spectrum between 15 and 60 Hz and the power below 15 Hz. While our findings are encouraging, we clearly want to emphasise that our results are site specific and only apply to wet-snow avalanches, since these were the only type of avalanche we investigated.

A comparison of the recorded seismic signals with calculated model parameters highlighted the importance of the interaction of the flowing snow mass with local terrain features for small to medium avalanches. Despite some discrepancies between the observed seismic signal and model output, our results show that it is possible to simulate small avalanches with RAMMS, which currently is mainly applied to

simulate large extreme avalanches. In the future, we plan to perform more such simulations to determine what the crucial parameters are to correctly simulate these small avalanches. Finally, for the upcoming winter, we plan on redeploying the seismic monitoring station and perform detailed field measurements (snow depth measurements at the release area, accurate gps measurements of the avalanche track, etc...) to investigate the validity of our results and improve the numerical modelling.

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