Study of avalanche dynamics by seismic methods, image-processing techniques and numerical models

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ABSTRACT. Seismic signals of avalanches, related video images and numerical models were compared to improve the characterization of avalanche phenomena. Seismic data and video images from two artificially released avalanches were analysed to obtain more information about the origin of the signals. Image processing was used to compare the evolution of one avalanche front and the corresponding seismic signals. A numerical model was also used to simulate an avalanche flow in order to obtain mean- and maximum-velocity profiles. Prior to this, the simulated avalanche was verified using video images. The results indicate that the seismic signals recorded correspond to changes in avalanche type and path slope, interaction with obstacles and to phenomena associated with the stopping stage of the avalanche, suggesting that only part of the avalanche was recorded. These results account for the seismic signals previously obtained automatically in a wide avalanche area.

INTRODUCTION

A study of the seismic signals produced by avalanches allows us to characterize them with a view to monitoring avalanches in areas or at times when human observation is not possible. This study is the first step towards designing a system for seismic automatic detection and recognition of avalanches in real time. In this regard, experimental devices for the automatic acquisition of seismic signals were installed during the last decade in the Catalan Pyrenees and French Alps (Sabot and others, 1995; Leprettre and others, 1996). The posteriori analysis of seismic signals obtained automatically over a wide avalanche-study area in the Pyrenees, by the Institut Cartogràfic de Catalunya since 1988, and attributed to avalanches indicates that only part of an avalanche is recorded (Sabot and others, 1995). The duration of these seismic signals ranged from 2 to 20 s, whereas the expected duration should exceed 40 s because the length of the avalanche paths in the study area was about 2 km. In order to explain this phenomenon and improve our understanding of these seismic signals, seismic data and video images of artificially released avalanches were recorded simultaneously. This has enabled us to control some of the information (duration of the avalanche, mean flux velocity, avalanche temporal evolution, etc.) which remains unknown when recording of naturally released avalanches is done without human observation. In this paper, we compare the seismic data and video images for two artificially released avalanches. In addition, we verify the avalanche simulation obtained by numerical modelling using these video images and analyse the seismic signals from the perspective of the modelling results.

SITE AND MEASUREMENTS

Our experimental site is at the Boí Taull ski resort (Pyrenees, northeast Spain), where the artificial release of avalanches is used to protect the ski area (Fig. 1). The two avalanches studied were artificially released by explosives during the 1995–96 season. The first (“Raspes Roies” path) was triggered at an altitude of 2725 m a.s.l. and ran down about 840 m over a regular open slope with a convex profile oriented towards the west; the vertical drop was about 500 m (Fig. 2a). The snow involved had a density that exceeded 200 kg m⁻³. The avalanche was dense and formed a powder cloud that did not travel very much further than the dense part; the deposit showed a rough aspect and included snow balls. The seismic station which recorded this avalanche was at the bottom of the avalanche path 1500 m from the explosion impact point.

The second avalanche (“Cervi” path) was triggered at an altitude of 2600 m a.s.l. and ran down 800 m with a vertical drop of 375 m (Fig. 3a). The snow involved had a density lower than 200 kg m⁻³ near the avalanche deposit. The avalanche ran over a sharp, convex slope rupture, incorporated air and formed a powder cloud. The deposit was rough

Fig. 1. Location map of the Boí Taull ski resort (northeast Spain).
and included snow balls about 1 m$^3$ in size. The seismic station was 900 m from the explosion impact point opposite the path.

The seismic signals and related video images were recorded using a common time base during both avalanches. The seismic signals were acquired in three dimensions using a standard seismic station with a sensitivity velocity response that was flat in the 2–40 Hz frequency band; the sampling frequency for the signals was 100 samples s$^{-1}$.

**SEISMIC STUDY**

**Ground-wave velocity**

The seismic records obtained in these experiments consist of
Comparision with video images

Comparison of the recorded seismic signals and the corresponding video images allows us to determine the origin of the different seismic wave trains. For this reason, the time base for these two types of information was shifted by taking into account the measured distances and the calculated mean ground-wave velocity.

The most prominent seismic waves generated by the “Raspes Roies” avalanche are shown in Figure 2b. No significant amplitudes corresponding to the avalanche are observed in the first 20 s after the explosion. The wave train of 12 s duration corresponds to images when the avalanche began to form a snow cloud and crossed the change of slope in the topography (1 in Fig 2). In this part, the maximum velocity of the avalanche was reached, as deduced from a simulation process. The wave trains of the last part of the signal correspond to the images of the avalanche-stopping stage, suggesting that the energy could be associated with the above mentioned stage (2 in Fig 2).

The vertical component of the seismic waves generated by the “Cervi” avalanche is shown in Figure 3a. In this case, it is possible to discriminate between the avalanche seismic signal and the ambient noise 25 s after the start of the avalanche. The first group of wave trains corresponds to the different impacts against the skilift masts (1–5 in Fig 3a and b), whereas the last wave train of this group (H in Fig 3) is associated with the impact of the flow against the maintenance hut for the skilift. Just as in the case of the “Raspes Roies” avalanche, the last part of the signal (A in Fig 3a) corresponds to the images of the avalanche-stopping stage.

NUMERICAL MODELLING USING VIDEO IMAGES

By studying the video images of the “Raspes Roies” starting zone and its stratigraphic profile, we observed that the powder part of the avalanche did not travel much further than the dense part, which is consistent with the density of the snow involved. In consequence, we consider that the powder part is negligible and assume the avalanche is dense for modelling purposes.

Numerical model

Numerical simulation is used in modelling avalanche dynamics. To this end, a number of models viewing the avalanche from a rigid body to a fluid have been considered for the different types of avalanches by different authors (Gubler, 1989; Marco, 1995).

A variety of two-dimensional models, considering the moving avalanche as a fluid flow or as a partially fluid flow have been tested by comparing different avalanche characteristics such as maximal flow velocities and run-out distances. The values obtained from the model computations have been compared with those measured in artificially released avalanches and in laboratory-scale avalanches (Gubler, 1987; Nishimura and Maeno, 1987).

In this study, the avalanche was modelled in three dimensions on the assumption that it was a Bingham body. The equations describing the flow were obtained by vertical integration of the balance laws of mass and momentum (Navier–Stokes equations) assuming the pressure was hydrostatic and the rheological model was that of Bingham (Naaim and Ancy, 1992). The equations obtained constitute a non-linear hyperbolic system and show the assumptions of the shallow-water equations. In order to determine the friction terms, it was assumed that the velocity profile was independent of depth, which allowed us to neglect dissipation. The system of equations which governs the motion of the avalanche is:

\[
\frac{\partial}{\partial t} \begin{pmatrix}
  h \\
  h u \\
  h v
\end{pmatrix} + \frac{\partial}{\partial x} \begin{pmatrix}
  h u \\
  h u^2 + \frac{1}{2} g \cos(\varphi) h^2 \\
  h u v
\end{pmatrix} + \frac{\partial}{\partial y} \begin{pmatrix}
  h u \\
  h u v \\
  h v^2 + \frac{1}{2} g \cos(\varphi) h^2
\end{pmatrix} =
\]

\[- g h \left( \sin(\varphi_x) \frac{\partial}{\partial x} + \frac{\partial}{\partial z} \right) \left( \sin(\varphi_y) \frac{\partial}{\partial y} \right) \left( \sin(\varphi_y) \frac{\partial}{\partial y} \right) = 0\]

where \( \partial ||\vec{u}||/\partial z = f(h,\mu,\tau_s) \), \( h \) is the flow depth at a point, \( z \) is the orthogonal axis of the terrain, \( \varphi_x \) and \( \varphi_y \) are the slopes in the \( x \) and \( y \) directions, respectively, \( \tau_s \) is the critical stress arising from the Bingham model and the mean velocity is \( \bar{u}(u,v,0) \).

Application to the “Raspes Roies” avalanche

The study was based on field observations. The topographic map of the domain was discretized as a regular mesh covering the whole surface. This was achieved by digitizing the contour lines of the study domain and using an interpolation method for meshing. The evolution of the mean and maximum velocities (calculated for each step and on the whole avalanche) (Fig 4) were obtained by taking into account the starting zone that was defined by the video images and the stratigraphic profile. A comparison between the simulated avalanche and the video images showed that the duration of the modelled avalanche was a little shorter than that observed, although the run-out distance was similar. The good results obtained in the simulation, in terms of the duration and run-out distance, allowed us to use the numerical model to understand the seismic signals from the avalanche. Comparison of the velocity profile of the simulated avalanche (Fig 4), the seismic signal (Fig 2b) and the video images showed that the first part of the signal (1 in Fig 2b) corresponded to the change in the topographic slope and also to that part where the maximum velocity of the ava-
The tracking algorithm makes use of the fact that the boundary between an avalanche and the rest of the image is the most energetic part of the image. Computation of the image energy and determination of its maximum variation allow us to adjust an initial contour to the real one.

The algorithm can be summarized as follows. A first contour as near as possible to the real one is selected. Subsequently, the searching contour algorithm is applied. This algorithm consists of (a) computing energies, (b) processing each point in accordance with the increase in energy, (c) adding or deleting points in order to respect the distance between the points and, finally, (d) cleaning up double points.

The tracking algorithm is naturally linked to the extraction contour algorithm. A block diagram of the algorithm is shown in Figure 5. For each image, we use a dilated contour of that obtained from the previous image to initiate the extraction contour algorithm. For this kind of image, where the maximum energy is reached by the tracking object, we are obliged to dilate the previous contour before processing the extraction contour algorithm. In terms of image processing, the algorithm introduces the idea of temporal smoothness in the energetic term.

Application to the “Raspes Roies” avalanche

The algorithm was applied to a sequence composed of 125 filmed images on the “Raspes Roies” avalanche, and the evolution of the avalanche tracked during its flow down the slope of the mountain. Three images are shown in Figure 6. In each of them the computed contour is traced with a white line. The first image (Fig. 6a) was taken at the start of the sequence, close to the initial contour, and the avalanche contour is perfectly defined. The second image (number 125 in the sequence) corresponds to the maximum extent of the avalanche. Its contour is always traced with precision (Fig. 6b). Finally, the third image shows different contours between the first image and the last one of the sequence (Fig. 6c). The results obtained indicate that the algorithm developed is well suited to our images, yielding very satisfactory results, and constitutes a validation tool for the numerical modelling of snow avalanches. Nevertheless, in order to improve the method, the sequence of contours must be mapped in three dimensions. This involves identifying a sufficient number of points on the image and on the Digital Terrain Model.

The similarity between the contours of the avalanche simulation and the video images, even when a change from two to three dimensions is not performed, confirms our conclusions about the validity of the simulation and consequently about the origin of the first part of the seismic signals of the avalanche. However, as the video images only consider the avalanche contour, this method cannot be used to account for the seismic signals generated during the avalanche-stopping stage.

CONCLUSIONS

Three different methods of avalanche analysis were applied simultaneously to an avalanche which occurred in the “Raspes Roies” path: seismic measurements, analysis of video images and numerical modelling were performed for the same event. The study has allowed us to account for the differences between the duration of the avalanche and that of the seismic signal. Only some parts of the avalanche generated seismic signals. The seismic signals recorded corresponded to changes in the avalanche type and path slope, interaction with obstacles and to phenomena associated with the stopping stage of the avalanche. These results ac-
count for the differences in duration of the avalanches and the corresponding seismic signals observed in records obtained automatically in real time without an observer. Moreover, numerical simulation of dense avalanches will be a useful tool in the absence of video images. Nevertheless, a transformation of the two-dimensional images into three-dimensional representation is necessary in order to achieve a direct comparison between the numerical models and the results of image processing.

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