Study of Seismic Signals of Artificially Released Snow Avalanches for Monitoring Purposes

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Abstract. Seismic signals generated by artificially released avalanches were studied from the seismological viewpoint in the time and frequency domains in an attempt to characterise them for monitoring purposes. The avalanches were artificially released and the corresponding seismic signals were recorded at different sites within a radius of up to 3 km together with the video images with a common time reference. The results obtained indicate that avalanches following the same path and recorded at the same site present similar seismic signals. A relationship between the avalanche seismic signals (amplitude, frequency content and wave trains) and the avalanche path was observed. The sources of the recorded seismic signals corresponds to avalanche path slope changes, interaction with obstacles and phenomena associated with the stopping stage of the avalanche. Local site effects were also present. These results lend support to the use of seismic signals as an efficient method of monitoring areas where avalanches are frequent and human observation is difficult.

1 Introduction

Snow avalanches are a natural hazard whose negative consequences have increased in recent times owing to the growth in activities and infrastructures related to skiing. Protection against avalanches by means of detection and/or warning is necessary for risk mitigation. Up to now a number of methods of detection and recognition of avalanches (human observers, cartography, lights...) have been applied either in real time or a posteriori. The methods acting in real time are of interest because they play a role in diminishing the risk in a short period of time. Seismic methods have proved to be a useful tool for the detection of avalanches in real time (Olivera et al., 1995; Sabot et al., 1995; Leprettre et al., 1996). However, some understanding of the avalanche seismic signals in relation to their sources (origin) is necessary to increase the rate of avalanche detection in areas or at times when direct human observation is not possible. To this end, experiments focused on improving our understanding of seismic signals generated by avalanches have been developed by our group (Sabot et al., 1998).

The present study was initiated in 1994 after the analysis of various signals, attributed to snow avalanches, which were obtained by means of an automatic seismic detector system. Contradictions between the duration of the seismic signals and the expected duration, bearing in mind the length of the avalanche path deduced by cartographic procedures, posed questions about the origin of the signals received (Sabot et al., 1995). This study is being carried out from the seismological point of view. The study has not been completed yet, but the results obtained to date point to some interesting conclusions.

2 Experiments

The experiments were designed to obtain a correlation between the seismic signals and the avalanche phenomena to gain a better understanding of the avalanche seismic signals in relation to their sources. The experimental procedure consisted in releasing avalanches artificially by explosives (by using cannon or helicopter) with a synchronised recording of both the corresponding seismic signals and the video images of the evolution of the whole avalanche. The seismic signals corresponding to the explosion and to the avalanche were obtained in 1 to 3 portable stations equipped with 3-D geophones (0.5 Hz or 2 Hz). The equipment was distributed in a radius of 1 to 3 km from the avalanche path with a geometry depending on the site characteristics. Characteristics of the evolution of the avalanches and an accurate cartography (1:5000/1:25000) of the avalanches were obtained "in situ", and in the laboratory analysing the video images. Snow characteristics (density, size and deposit distribution) were

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Fig. 1. The Núria ski resort experimental site. Cartography of the avalanches corresponding to the experiments of 24th January 1996 and 1st February 1996. The limits mapped are the maximum limits of the avalanches.

Table 1. Characteristics of the Núria experiments. Aval.: avalanche number; Date: date of the experiment; Av. type: type of avalanche; D*: avalanche without aerosol, but not very dense flow (density of the snow before the release between 120 kg/m^3 and 150 kg/m^3); Length: approximate length from the highest point of the avalanche to the maximum run-out point; UB1/UB2/UB3: seismic stations (Figure 1). Crosses: recorded signals. Dashed areas: avalanche signals discussed.

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obtained, when possible, immediately after the experiments. We used the infrastructure and facilities of the ski resort of Vall de Núria (Ferrocarris de la Generalitat de Catalunya) in the eastern Pyrenees (Spain) and the equipment of the Avalanche experimental site in Vallée de la Sionne (Switzerland). This experimental site, which belongs to the Swiss Federal Institute for Snow and Avalanche Research, is equipped with various avalanche measuring instruments (Issler, 1999).

In Fig. 1, where the main characteristics of the site of Núria are shown, the potential starting zones together with the cartography of the avalanches studied are indicated. The avalanches were triggered off in the 1996 winter season and were recorded at different seismic stations. The location of the seismic portable stations used in the experiments are indicated by dots and the shooting points by stars. Video images were obtained in most cases. The main characteristics of each of these avalanches and experiments are indicated in Table 1 together with their corresponding explanation.

The starting zones and the cartography of the avalanches artificially released at the Avalanche experimental site in Vallée de la Sionne are presented in Fig. 2. The avalanches were recorded in 1996, 1997 and 1999 winter seasons. The location of the recording seismic stations for the experiments and the corresponding shooting points are indicated in Fig. 2. The main characteristics of the different avalanches and experiments are given in Table 2 together with their corresponding explanation.

3 Signal study procedure

The seismic signals were homogenised, being converted to the actual ground motion velocity (m/s). All the signals were filtered with a 2-50 Hz band pass filter to compare the signals since different types of seismic equipment were used for the data acquisition. The sampling ratio of the signals was 100 samples per second.

Figure 3 shows the seismograms of the three components (vertical, N-S and W-E) of the ground motion velocity corresponding to the 1997 Pointe des Tsarmettes (PdT-97) avalanche, which is a typical seismic recording obtained in our experiments. The vertical axis corresponds to the ground motion velocity and the horizontal axis is time. The seismic records consist of two differentiated parts: an earlier signal produced by the explosion and a later signal due to the avalanche. There is a lapse of time between them. The explosion signal is composed of three different wave trains which are easy to identify in accordance with their arrival time: the waves propagating on the ground, the air waves (high amplitude sound waves caused by the blast) and their corresponding echo waves. Site characteristics (wave velocity propagation and local effects) were obtained from the difference between the arrival times of the ground and...
air wave trains of the explosion, the cartography and the video images. These data enable us to determine the corresponding shifting between the seismic signals recorded at different sites and the video images. Time and frequency analyses and the study of the ground particle movement for the different wave trains were performed after identification by using video images of the avalanche evolution. The seismic noise of the different sites before, during and after the experiment (frequency and time domain) was analysed prior to the identification of the avalanche signal wave trains.

### 4 Results and discussion

The source of the avalanche seismic signals was identified in an earlier study (Sabot et al., 1998). Thus, where obstacles (trees, constructions, ski lifts...) are present in avalanche paths, the energetic avalanche seismic wave trains are associated with the impacts on these. By contrast, where obstacles are absent, the avalanche seismic signals correspond to changes in the avalanche path slope, to alterations in the type of flow or avalanche type, and to phenomena associated with the stopping stage of the avalanche. This conclusion was also reached in a study on avalanches carried out in Russia in 1990 (Firstov et al., 1992). Our studies indicate, moreover, that the wave trains generated in these cases are different (time and frequency domains) (SurirIach and Sabot, 1999; SurirIach et al., 1999). Two types of these wave trains are shown in Fig. 3. Wave trains associated with changes in the slope, indicated by 1 in Fig. 3, are long wave trains (exceeding 10 s) whereas those associated with the stopping phase, which are indicated by 2, are various short wave trains (1 to 5 s each one).

Another finding in relation to the source of the seismic waves is that waves corresponding to the beginning of the avalanche were not observed. We did not detect these waves in the experiments that were specifically designed for this purpose or in other experiments carried out. Figure 4 shows a detail of the seismograms corresponding to the 1999 Crête Besse avalanche (CB2-99) and recorded at stations T and H (Figure 2). Note that station T is in the path of the avalanche. In this figure only the first part of the avalanche signals is represented with the arrival time of the explosion waves propagating on the ground considered as common origin of time. The most energetic seismic component of each of the two sites is depicted. In this figure it is possible to observe a time lapse between the explosion signals and the arrival of the energetic waves. This is observed not only in the signals recorded at station H (at some distance from the beginning of the avalanche), but also in the signals recorded at station T nearer the start of the avalanche, although the time lapse is shorter given the shorter distance between the avalanche and station T.

A possible explanation for this is that a given amount of snow making up the avalanche is necessary to generate sufficient seismic energy for it to be detected by the instruments.

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**Table 2. Characteristics of La Sionne experiments.**

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**Fig. 2.** The La Sionne experimental site. Cartography of the avalanches corresponding to the experiments of 15 February 1996 and 16 February 1997 at Pointe des Tsarmettes and 30 January 1999 at Crête Besse 2. All the avalanches were mixed powder and dense snow avalanches. The limits mapped are the maximum limits of the avalanches and include both dense and powder parts. In the case of Pointe des Tsarmettes, the dense part of the 1996 avalanche stopped at about 2000 m a.s.l. whereas the dense part of the 1997 avalanche stopped at about 1800 m a.s.l., the former being smaller than the latter. Arrow indicates the slope rupture referred in the text.
Pointe des Tsarmettes 1997 Avalanche

Fig. 3. Three component seismograms (vertical, N-S and W-E) converted to actual ground motion velocity of the 1997 Pointe des Tsarmettes avalanche recorded at site S (Figure 2). Signals of the explosion and avalanche are indicated. Part 1 corresponds to changes in the slope and part 2 to the stopping phase. Origin of time: arrival time of the explosion waves propagating on the ground.

Creta Besse 1999 Avalanche

Fig. 4. First part of the seismograms of the 1999 Creta Besse avalanche recorded at stations T (N-S component) and H (W-E component). Common origin of time: arrival time of the explosion waves propagating on the ground in each site.
Fig. 5. Detail of the three component seismograms and their spectra of the Pointe des Tsarmettes avalanches recorded in 1996 (PdT-96) (top) and in 1997 (PdT-97) (bottom) at station S which corresponds to changes in the slope (arrow in Fig. 2). In each case, time origin is the arrival time of the explosion waves propagating on the ground. The ground motion velocity in the vertical (Z-E and Z-N) and horizontal (N-E) planes of selected wave trains (in bold) are also depicted. Predominant direction in each of these planes is indicated by a line.
In addition to the above results, which are useful for monitoring purposes, the analysis of the seismic signals yields information which is also useful in this regard. A relationship exists between the avalanche seismic signals and the avalanche path in terms of reproducibility (in the time and frequency domains) i.e., avalanches following the same path and recorded at the same site present similar seismic signals. The signals in Fig. 5, which correspond to a detail of the avalanche seismic signal of the Pointe des Tsarmettes avalanches recorded in 1996 (PdT-96) and in 1997 (PdT-97) at station S (Figure 2), illustrate this effect. These two avalanches followed the same path and the detail corresponds to the slope rupture located between 2300 m a.s.l. and 2450 m a.s.l. (arrow, Figure 2).

Regardless of the amplitude of the signal (ground motion velocity), the distribution of the seismic energy and the spectra content of the three components of the signals of the PdT-96 and PdT-97 avalanches are similar. The ground motion velocity in the horizontal (N-E) and vertical (Z-E and Z-N) planes of selected wave trains are also depicted in Fig. 5. A predominant direction is observed in each of these planes, which is similar for both avalanches. This effect is associated with the source of the signals. This figure also demonstrates that a correlation exists between the avalanche size and the seismic signal characteristics. Avalanche PdT-97, which was larger than PdT-96, has a ground motion velocity signal whose amplitude is larger than that of PdT-96, although the frequency content is similar (Figure 5).

The comparison of the signals obtained in different experiments carried out at the Núria experimental site, moreover, yields some results related to the existence of local site effects. A different distribution of the seismic energy in the three components of the ground motion velocity is evidenced in the signals corresponding to the same avalanche but recorded at different sites. The horizontal (N-S) component of the ground motion velocity for avalanche 3a recorded at station UB2 is the most energetic of the three components. By contrast, the ground motion velocity energy is similarly distributed in the three components at station UB3 (Figure 6). This shift of energy from one component to another is caused by the different partitioning of the seismic energy at the various surface ground discontinuities and to scattering processes due to lateral heterogeneities of the ground (i.e. topography). This is a phenomenon which is observed in wave propagation. For a deeper insight into this subject see, for example, Hestholm and Ben Ruud (1998). Distinctive features of each avalanche in terms of seismic signals are also observed i.e., signals from various avalanches recorded at the same site show some differences.

5 Conclusions

The use of artificially released avalanches has proved to be a useful tool for the comparative study of avalanche seismic signals. This not only allows us to characterise the study area analysing the signals generated by the explosion but also to control the information of the video images.

The reproducibility of the avalanche seismic signals in relation to the avalanches and the specific trends of the avalanches obtained from the analyses of the data in the time and frequency domains enable us to draw a number of conclusions that are worth considering for monitoring purposes.

The analysis of the seismic signals generated by avalanches demonstrates the existence of a relationship between the avalanches and the characteristics of their seismic signals (shape, amplitude and frequency content). Our findings reinforce our confidence in the use of seismic signals as a method of controlling the avalanche phenomena in areas
where human observation is not possible. Nevertheless, given the presence of local site effects, a characterisation of the avalanche path in relation to the monitoring sites is necessary. Moreover, the lapse of time between the start of the avalanche and the arrival of the energetic waves should be borne in mind in avalanche detection. This, together with the shift of the seismic energy from one component of the ground motion to another depending on the avalanche and the site (not all the three components have the same energy), should be considered for monitoring purposes given that in cases where only a 1-component sensor (frequently the vertical component) is used to monitor an area, the measured component of the ground motion might not have the largest amplitude, resulting in a delay in the avalanche detection.

The obtained relationship between the avalanche size and the amplitude of the signals opens up the possibility of estimating the size of the avalanche (involved volume and length) on the basis of the amplitude of the signals. Nevertheless, the estimation of the size is not an easy task owing to the presence of local site effects. In the case of establishing a scale of avalanches a priori monitoring of the different sites is necessary in order to eliminate these effects.

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References


