Spanish avalanche research: experimental sites and seismic measurements

Recherches espagnoles dans le domaine des avalanches: sites expérimentaux et mesures sismiques

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ABSTRACT: Seismic signals generated by avalanches have been studied by the avalanche team of the Universitat de Barcelona since 1994. The aim of the study is to understand the avalanche seismic signals in relation to their sources to obtain information on the avalanche dynamics and hence use seismic measurements for monitoring purposes. To this end, experiments focused on improving the knowledge of seismic signals generated by avalanches have been carried out by our group. The infrastructure and facilities of the ski resort of Vall de Núria (Ferrocarrils de la Generalitat de Catalunya) and Boí Taüll in the eastern Pyrenees (Spain) and the equipment of the Avalanche experimental site in Vallée de la Sionne (Switzerland) have been employed. The study of the seismic signals generated by the avalanches is undertaken from the viewpoint of seismology in the time and frequency domains. Our procedure and some of the results of our research are presented.

KEY WORDS: seismic signals, snow avalanches, seismic detection.

RÉSUMÉ: Les signaux sismiques produits par des avalanches sont étudiés par l'équipe avalanche de l'Université de Barcelone depuis 1994. Le but de ces études est de comprendre les signaux sismiques d'avalanche en relation avec leurs sources pour obtenir l'information sur la dynamique de l'avalanche et par conséquent pour utiliser les mesures sismiques pour la détection et la surveillance. À cet effet, les expériences ont été centrées sur l'amélioration de la connaissance des signaux sismiques produits par des avalanches. L'infrastructure et les équipements de la station de sports d'hiver de Vall de Núria (Ferrocarrils de la Generalitat De Catalunya) et de Boí Taüll dans les Pyrénées Orientales (Espagne) et l'équipement du site de la Sionne (Suisse) ont été utilisés. L'étude des signaux sismiques produits par les avalanches est entreprise du point de vue de la sismologie dans les domaines de temps et de fréquence. Notre procédé et certains des résultats de notre recherche sont présentés.
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1. Introduction

Seismic signals generated by avalanches have been studied by the avalanche team of the Universitat de Barcelona (U.B.) since 1994. The U.B. group was previously engaged mainly in cartographic studies in relation to spatial prediction of snow avalanches in the western Catalan Pyrenees. This activity, which was initiated in 1986-1987, was based on a collaboration between the U.B. and the Institut Cartogràfic de Catalunya. Part of the U.B. group is also working on the cartography of snow avalanches in the Eastern (Catalan) Pyrenees and in Andorra ([FUR 95]; [FUR 98]).

Our seismic studies were initiated in 1994. We decided to study the seismic signals generated by avalanches released artificially in an attempt to resolve some contradictions that arose after the analysis of various seismic signals attributed to snow avalanches. These signals were obtained by means of an automatic seismic detector system [SAB 95], which was installed for detection purposes in an area where direct human observation were not possible. 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. These contradictions must be resolved when developing a successful detection system. Seismic equipment has proved to be a useful tool for the detection of various natural phenomena such as debris flow or avalanches [WEI 94]; [SAB 95]; [LEP 96]; [NIS 97]; [ARA 99]). However, in contrast to the debris flow where the flux is very canalised, snow avalanches can occur on more open slopes. This, together with the varying size of the avalanches, poses a number of problems for their optimum detection: medium-sized to small avalanches are more difficult to detect than the larger ones. To improve the detection algorithms of automatic avalanche detection, a fuller understanding of the seismic signals in relation to their sources is necessary.

The study of the seismic signals produced by controlled avalanches allows us to control the relationship between the seismic signals and the avalanche phenomena and hence to understand avalanche seismic signals in relation to their sources. The study of the seismic signals, moreover, yields further information on the avalanche phenomena, which can be useful for modelling. Our procedure and some of the results of our research are presented here.

2. The experiments

Our experimental procedure has evolved with time. Initially, the experimental procedure consisted in artificially releasing avalanches by explosives (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 [SAB 98]. In most cases the seismic signals corresponding to the explosion were also obtained in addition to the avalanche seismic signals. These signals together with a good cartography and the video images allow us to obtain site characteristics (velocity propagation of the waves and local site effects) and to identify the different avalanche wave trains in relation to the avalanche (time domain) [SAB 98]. 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 obtained, when possible, immediately after the experiments. Although this type of experiment is still ongoing, another experimental procedure is currently being set up. This consists in installing the equipment on the path over which the avalanche passes. This installation seeks to obtain information on the parameters of the avalanche at short distances when it passes over the sensor. Standard seismic equipment used in seismological studies is employed. This allows us to avoid problems related to the normalisation of the data.

3. Experimental Sites and avalanches

To carry out the experiments, we have used the infrastructure and facilities of the ski resort of Vall de Núria (Ferro carrils de la Generalitat de Catalunya) and of Boí Taüll both 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 instruments for measuring avalanches [ISL 99]. We are currently using the Núria and the Vallée de la Sionne sites.

Experiments in the Boí Taüll ski resort (Pyrenees, NE Spain) were carried out during the season 1996/1997. Two artificially released avalanches were recorded. The first avalanche (Raspes Roies path) was dense and developed a powder cloud that did not travel very much further than the dense part; the deposit presented a rough aspect and included snow balls. The seismic station, which recorded this avalanche, was located at the bottom of the avalanche path (Figure 1). The second avalanche (Cervi path) ran over a sharp, convex slope rupture, incorporated air and formed a powder cloud (Figure 2). In this case the avalanche struck the ski lift, which was in its path. Further details of these avalanches can be obtained in [SAB 98].

![Figure 1. Cartography of the “Raspes Roies” avalanche on I.C.C. map scale 1:5000. E: explosion impact point (2720 m a.s.l.), S: seismic station (2090 m a.s.l.). 1: Zone where the avalanche slope and the avalanche type change. 2: Avalanche stopping zone (Cartography G. Furdada).](image-url)
The avalanches at the Núria site, which are normally small in size, were recorded at different portable seismic stations never reached by the avalanches. Figure 3 shows the general topography of the site, which consists of an open slope of low surface roughness. Some cliffs and gentle channels that separate the different starting zones are present in the highest part of the slope. Details of this site and the recorded avalanches are in [SUR 99a] and [SUR 00].

Figure 2. Cartography of the "Cervi" avalanche artificially released at Boí Taüll experimental site (1996) on the I.C.C. map (scale 1:5000). 1 to 5: ski lift masts. E: explosion impact point (2600 m a.s.l.); S: seismic station (2260 m a.s.l.) (Cartography G. Furdada).

Figure 3. Núria ski resort experimental site. Potential starting zones and cartography of the avalanches of the experiments of the 24th January 1996, 1st February 1996 and 10th January 1999. The limits mapped are the maximum limits of the avalanches (Cartography G. Furdada).
The starting zones and the cartography of the avalanches artificially released at the Avalanche experimental site in Vallée de la Sionne are presented in Figure 4. Note the different scale of this site in relation to the aforementioned sites. The location of the recording seismic stations for the experiments and the corresponding shooting points are shown in the figure. In the winter seasons 1996 and 1997 the Pointe des Tsarmettes avalanches (PdT-96 and PdT-97) were artificially released. Avalanches of varying size followed almost the same path and were recorded at the same seismic station S. Two stations have been installed at this experimental site since 1998: station T in a cavern in the track and station H at the end of the path. Station H has worked continuously since 1999 and station T since the 2000-2001 winter season. Thus, both stations record the events continuously throughout the winter seasons, allowing us to obtain the signals not only of the artificially triggered avalanches but also those of the natural avalanches. Two more seismic stations belonging to the SLF are also located at the site: station A at 2275m in the track (not indicated in the figure) and station B in the same place as T (Figure 4). The avalanches recorded in the Vallée de la Sionne have been mixed dense and powder snow flows to date. Details of the experiments are in [SUR 00].

Figure 4. La Sionne experimental site. Starting zones and cartography of the avalanches at Pointe des Tsarmettes (PdT) and at Crête Besse 2 (CB2-99). All the avalanches were mixed powder and dense flows. The limits mapped are the maximum limits of the avalanches and include both dense and powder parts. The slope ruptures generating seismic signals discussed in the text correspond to the cliffs indicated by arrows (Cartography G. Furdada).
4. The seismic study

Figure 5 shows a typical seismic recording obtained from our experiments. It shows the seismograms of the three components (vertical (Z), N-S and W-E) of the ground motion velocity corresponding to the 1997 Pointe des Tsarmettes (PdT-97) artificially released avalanche. The vertical axis corresponds to the ground motion velocity and the horizontal axis is time. The seismic records consist of two 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.

![Figure 5. 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 4). 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.](image)

The study which is carried out from the seismological point of view consists of a) determination of the actual ground motion (conversion mV to m/s); b) control of the seismic noise of the recording site before, during and after the experiment (frequency and time domains); c) determination of the seismic characteristics of the site (estimation of wave propagation velocity, local site effects); d) identification of the different avalanche signal wave trains in relation to the video images (time domain); e) time and frequency analyses of the totality and the different parts of the signals; and f) the study of the ground particle movement for each wave train. The methodology used is reported in [SAB 98] and
Snow and avalanche test sites in [SUR 99b] [SUR 99c]. We are currently analysing the signals by means of their running spectra [BIE 02a] [BIE 02b] in addition to the total spectrum of the signals.

![Figure 6](image.png)

**Figure 6.** Seismograms of the vertical, north-south and east-west component of the "Raspes Roies" avalanche (Figure 1). Part 1 corresponds to changes in the slope and part 2 to the stopping phase Origin of times corresponds to the explosion (explosion signals have been excluded). Vertical axis: ground velocity (μm/s).

5. Results

Different results have been obtained up to now from the experiments. Some of them are presented below.

5.1. Reproducibility

Reproducibility is an important factor in any experimental procedure because it allows us to confirm the results and to give weight to the conclusions. In our analysis of the signals we observe a relationship 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. We obtain this result from different experiments and at different sites.

This reproducibility has also been observed at different time scales (detailed and total signal) [SUR 00]. More recently the reproducibility has also been obtained using the
running spectra of the signals [BIE 02b]. Reproducibility is important in terms of interpretation and analysis of the events given that a connection between the signals and the avalanches is implied.

5.2. The source of the signals

The source of the avalanche seismic signals has been identified in an earlier study where image processing techniques and numerical models were used [SAB 98]. Thus, in avalanche paths where obstacles (trees, constructions, ski lifts...) are present, the energetic seismic wave trains are associated with the impacts on these. By contrast, in the absence of obstacles, the energetic seismic signals correspond to a) changes in the avalanche path slope, b) alterations in the type of flow or avalanche type, and c) to phenomena associated with the stopping stage of the avalanche. In subsequent studies of small to medium sized avalanches [SUR 99c; [SUR 00]], we showed that the energetic wave trains generated by the different mechanisms stated above were different in the time and frequency domains. Two types of these wave trains are shown in Figure 5 and in Figure 6. Figure 5 corresponds to the 1997 Pointe des Tsarmettes avalanche (Figure 4) whereas Figure 6 corresponds to the Raspes Roies avalanche (Figure 1). Both avalanches differed in size and followed different paths but the signals present the same behaviour. Wave trains associated with changes in the slope, indicated by 1, 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) with high amplitudes. All these results were obtained by records from stations placed at some distance from the avalanche. These results account for the differences in duration between the avalanches and the corresponding seismic signals observed in records obtained automatically [SAB 95].

Another finding in relation to the source of the seismic waves is that waves corresponding to the beginning of the avalanche are not observed in our experiments. When the instruments are at some distance from the avalanche we did not detect these waves in the experiments that were specifically designed for this purpose or in other experiments carried out. Figure 7 displays the first seconds of the most energetic component of the seismograms of the CB2-99 (Vallée de la Sionne) avalanche (Figure 4) recorded at station T (N-S component) and at station H (E-W component) with the arrival time of the explosion waves propagating on the ground as common origin of time. Note that station T is in the path of the avalanche. This figure shows that signals of the avalanche recorded at station T have larger amplitudes than those recorded at station H. A time lapse between the arrival of the explosion waves and that of the earliest detectable signals from the avalanche (E1, E2) is observed although this time lapse is shorter at T (11 s) than at H (22 s). The energy observed (E1) in the seismogram recorded at T station corresponds to the passing of the avalanche over the slope rupture at 2500 m altitude (A11', Figure 4). The corresponding signal at station H is not observed at the same arrival time although the waves must have arrived (wave propagation velocity in the ground about 4000 m/s). The subsequent energetic waves (E2) observed at station H, which are also observed at station T (E’2), correspond to a change of the type of flow (aerosol is developed) at approx. 2250 m altitude (A22’, Figure 4). We account for the delay of the arrival of the energetic waves at the two stations as follows: a lapse of time is necessary (given the attenuation of the amplitude of the seismic waves as a function of the distance) for the avalanche to gain enough kinetic
energy in order to generate sufficient seismic energy to be detected. The greater the distance source-station, the longer the lapse of time for the avalanche to be detected.

Figure 7. First part of the seismograms of the 1999 Crèta Besse (CB2-99) avalanche recorded at stations T (N-S component) and H (W-E component). E1, E2 and E’2 correspond to earliest avalanche signals detected. The arrival times at different heights are indicated according to the arrival times deduced from Doppler radar and video measurements (personal communication from Issler, D., Gruber, U., Dawes, N. and Dufour, F., January 2000). Common origin of time: arrival time of the explosion waves propagating in the ground to each site.

5.3. Local site effects

Another important factor in relation to the signal's source is the existence of local site effects. These effects are observed mainly in small to medium-sized avalanches. 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. Thus, Figure 8 presents the most energetic part of the signals generated by avalanche 3a recorded at stations UB2 and UB3 (Figure 3), together with their spectra. These stations were located at a similar distance from the avalanche. At station UB2, the signals in the time domain show that the horizontal (N-S) component of the ground motion velocity is the largest of the three components. By contrast, at station UB3, the ground motion energy is similarly distributed in the three components. Moreover, the frequency content of the components at UB3 is lower than that of those in UB2. The diverse features of the signals depending on the recording site reflect an energy shift from one seismic component to another. This is due to the partitioning of the seismic energy by refraction and reflection at
the surface and various ground discontinuities and by scattering processes caused by lateral heterogeneities of the ground (i.e. topography). This consideration should be taken into account for monitoring purposes [SUR 01]. It is possible that the measured component of the ground motion does not have the largest amplitude, which would result in a delay or in a failure (in the case of small-sized avalanches) to detect the avalanche. This conclusion is more important in the case of small to medium-sized avalanches where the signal to noise ratio is usually lower than in the case of larger avalanches.

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**Figure 8.** Detail of the three component seismograms (Z, N-S and W-E) and their spectra corresponding to Núria avalanche 3a recorded at stations UB2 (left) and UB3 (right) (Figure 3).

6. Considerations for using the seismic signals as a measure of the avalanche size

The relationship between the avalanche size and the amplitude of the signals [SAB 98], [SUR 01], [BIE 02] offers the possibility of estimating the size of the avalanche (volume and length) on the basis of the amplitude of the signals. Nevertheless, a number of factors should be borne in mind. First of all, seismic energy can be focused in one direction because of site effects. This should be taken into account in cases where only a 1-component sensor (frequently the vertical component) is employed to measure the amplitudes. It is possible that the measured component of the ground motion does not have the largest amplitude, which would result in a erroneous value when determining the amplitude. A prior monitoring of the different sites in relation to the avalanches is necessary to avoid problems. These considerations are more important in the case of small to medium-sized avalanches than in the case of large avalanches.

The type of avalanche (dense, mixed, powder…) should also be kept in mind when scaling. We noted that a pure powder snow avalanche, which was larger in extension than a dense avalanche observed under similar conditions, had a signal of smaller amplitude despite having a similar frequency content [SUR 01]. It is therefore necessary to consider
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the avalanche type when scaling avalanches by means of the signal amplitude. Another factor that should be borne in mind is the correction factor due to the different distance avalanche -sensor.

7. Recent studies

Our results were obtained from more than 30 records of snow avalanches varying in size and type. Most of this signals were recorded at some distance from the avalanche. The results obtained are mainly used for detection purposes. Although these studies are ongoing, we are currently studying the signals produced by avalanches that pass over the sensor. Our current line of research is directed to using the high frequency band of those signals to obtain characteristics of the avalanche[BIE 02].

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