OVERVIEW OF THE 1999 MEASUREMENTS AT THE SLF TEST-SITE VALLÉE DE LA SIONNE

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ABSTRACT: Three large avalanches were artificially triggered on January 30th, February 10th and February 25th 1999, at the Vallée de la Sionne test site of the Swiss Federal Institut for Snow and Avalanche Research (SLF). This paper presents an overview of the recorded measurements and discusses the quality of each measurement method. Two automatic stations measured the weather and snow conditions continuously at the site during the whole winter. Avalanche velocities were measured using Doppler radar that were positioned in a bunker on the foot of the opposing slope. In addition, video recordings were taken from different observation points. Along the avalanche track, three pairs of FMCW radar were buried in the ground to measure flow depths and entrainment/deposition rates. Pressure measurements were taken on both, a 21m high, oval-shaped pylon and a wedge in the lower part of the avalanche track. Snow volume were measured with photogrammetric methods. The size of the avalanches increased chronologically. The last avalanche of February 25th had a width of more than one kilometre and a mean fracture depth of about 2.1m. This avalanche burried the shelter on the foot at the opposite side of the avalanche with more than 4m of snow. The overall deposition volume of all three avalanches was more than 1'300'000m^3. Some of the obstacles were destroyed, since the avalanches were much larger than assumed design loads.

KEYWORDS: Avalanche deposits, avalanche dynamics, avalanche modelling, avalanche velocities, impact forces, avalanche experiments, avalanche forces.

1. INTRODUCTION

Since December 1997 a new Swiss test-site for avalanche dynamics experiments has been operational by the Swiss Federal Institute for Snow and Avalanche Research, SLF, Davos, in the community of Arbaz, Canton VS (Ammann, 1998). The objective of this site is to study the overall dynamic behaviour of dense-flow and powder-snow avalanches and to measure avalanche impact forces. In the first winter 1997/98 no avalanche had been released due to the lack of large snowfalls. However, in Winter 1998/99 three periods of intensive snowfall occurred in the European Alps. At the end of each of these periods one large avalanche was triggered by explosives. Each of these three avalanches can be considered an extreme event. The avalanches occurred at the same time and under the same conditions as the many other catastrophic avalanches that struck the European Alps (Wilhelm et al., 2000).

In this paper the measurements taken on these avalanches are summarised. Firstly, the meteorological conditions leading to these extreme avalanches are described, followed by an overview of the perimeters of the events. Then, the measurements of avalanche velocities, volumes, pressures and impact forces are described. In the conclusions the most important results of all the measurements with respect to avalanche dynamics and avalanche hazard mapping are discussed and an outlook about future improvements on the measurement devices is given.

2. METEOROLOGICAL CONDITIONS

The automatic weather station "Donin du Jour" of the IMIS-network (Russi et al., 1998), recorded the evolution of the snow cover and the meteorological conditions during the whole winter. It is located only two kilometres to the north of the release area of the experimental site The wind speed and temperature were measured directly at the top of the release area. Until the beginning of the first of the three large snowfall periods, the snow cover depth was below the annual average. Figure 1 shows the development of the snow

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cover depth and the temperatures for the time period between January 26th and February 26th. The three main snowfall periods are easily recognisable. Strong north-westerly winds accompanied the snow falls and led to fracture depths that were much higher than the snow depths measured on the neighboured flat field where the automatic station is located. The maximum measured wind speed was in the first period above 100km/h, in the second 80km/h and the last 70km/h. The triggering dates, January 30th, February 10th and February 25th were the first days without snow fall and – even more importantly for some of the measurements – without any clouds.

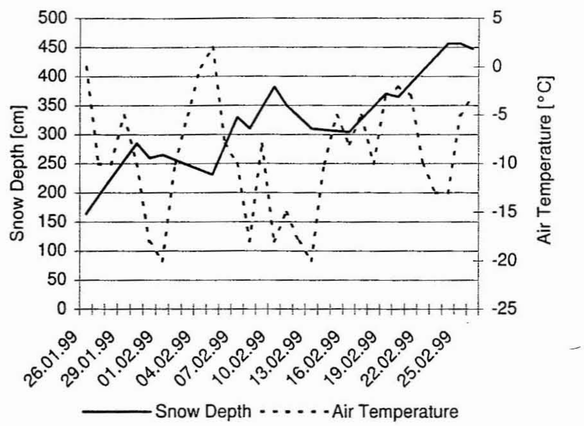

Figure 1: Snow depth and air temperature between January 26th and February 26th 1999 as measured by the automatic station "Donin du Jour" at an altitude of 2390m a.s.l., 2km north of the avalanche release area.

The temperature during the first two snowfall periods was around –10°C or lower. Therefore, the new snow along the whole track was dry and loose. The snow densities measured on the day of the triggering in the release area were about 200kg/m^3. At the third period, around February 20th, warm air led to rainfall up to an altitude of 1600m a.s.l. and to higher densities and moisture of the snow along the track. For this avalanche the density of the snow cover at the fracture line was about 240kg/m^3.

3. OVERVIEW OF THE EVENTS

The perimeters of the three avalanches are shown in Figure 2. On January 30th about the half of the maximum foreseen release area fractured. On February 10th the southern end of the avalanche fracture line exceeded the instrumented test site by about 600m. On February 25th the avalanche covered exactly the whole foreseen release zone. Due to the high fracture depth of about 2.1m over a length more than 1km the deposition area exceeds the expected runout by more than 500m. The avalanche destroyed forests along the track as well as in the runout area.

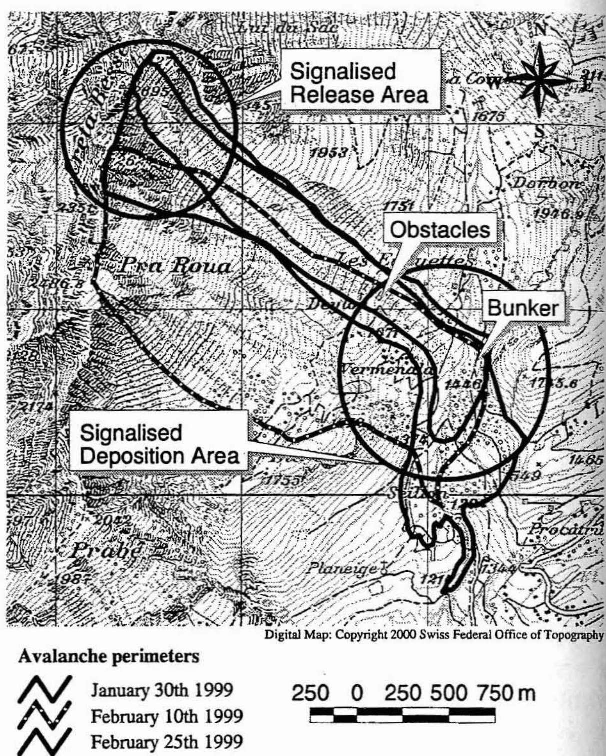

Figure 2: Perimeters of the avalanches of January 30th, February 10th and February 25th 1999.

4. VELOCITY AND FRONT-POSITION MEASUREMENTS

The velocities of the avalanches were measured by four constant-frequency radars. They were emitting frequencies between 9.3 and 10.17 GHz (X-Band) and sampling the reflected signal at a rate of 15.049kHz.

Radar waves were reflected by snow particles with a minimum size equal to a fraction of the radar wavelength. X-Band radars can see particles larger than a few millimetres. The received signal is mixed with the signal being sent. Its low-frequency part contains the Doppler frequency sought for. As the amplitude of the signal can vary by several orders of magnitude, the signal and the logarithm of its magnitude are separately recorded. For data analysis, the signal may be split up into the different frequency shift components by means of a Fourier transformation. These frequency spectra are known as the Doppler spectra, i.e. the distributions of the velocities of snow particles in the avalanche for specific times across the width of sight of the radar. Depending on the opening angle of the radar beams, these distributions give an overview of the speed of the entire avalanche or only a part at this time.

Figure 3 shows for each avalanche a representative amplitude-velocity spectrum at the time when the avalanche reaches the lower part of the track, where the obstacles are located.

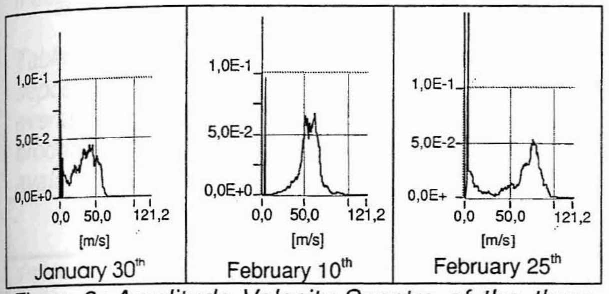

Figure 3: Amplitude-Velocity-Spectra of the three avalanches at the lower part of the track (9.3 GHz-radar).

Since the Doppler spectra show a wide range of velocities they need to be carefully interpreted. In general the low speed parts of the spectrum represent velocities of the tail of the avalanche or of a secondary avalanche. The velocities at the maximum amplitude represent the speed of most particles. It may or may not be the front velocity of the avalanche. On the right hand side of the maximum amplitude the Doppler Spectra contain the maximum (peak) velocities of particles of more than 1mm.

On January 30th the spectrum show a very large velocity distribution with a maximum amplitude between 40 – 50 m/s. The maximum velocities are about 65m/s. The spectrum of February 10th has a higher amplitude with velocity range between 50 and 60m/s and a more uniform velocity distribution. The reason for this finding is that the avalanche flow was concentrated in one single gully and could not spread in the same way as the two other avalanches did. The maximum velocities reached about 80m/s. The avalanche of February 25th had its maximum amplitude at a velocity of about 75m/s. The spectrum is remarkable wider than the one of February 10th with maximum velocities up to 110m/s.

The spectra in Figure 3 represent only one specific time period of the avalanche flow. For every time period of the avalanche flow these spectra can be plotted. However, the difficulty of the Doppler spectra is to localise the measured velocities within the avalanche. To complement this information, the video recordings are used to localise the avalanche front positions over time.

For this purpose the video images have to be georeferenced. In a first step reference points have to be found that are visible in the digitised video images as well as its co-ordinates known in the terrain. In a second step, the distortions caused by the camera and the terrain are rectified using the digital terrain model and the ERDAS OrthoBASE Tool (ERDAS, 1999). In Figure 4 the front positions of the February 25th avalanche are shown.

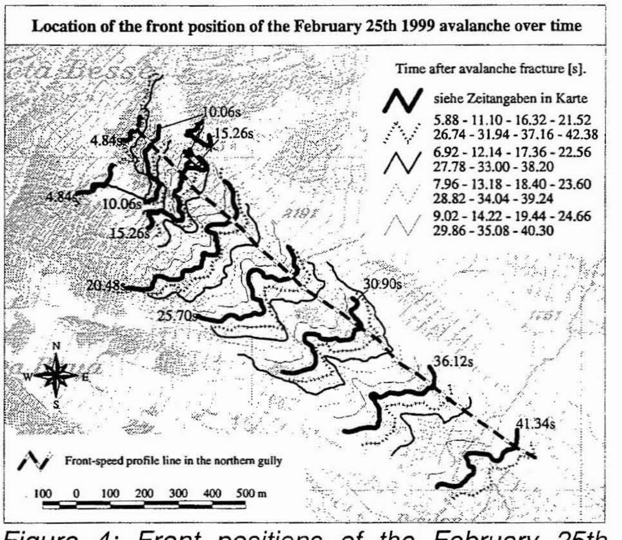

Figure 4: Front positions of the February 25th 1999 avalanche in an interval of about 1s. The line in the northern gully of the avalanche indicates the location of longitudinal section of Figure 5.

The accuracy of the localisation of these front positions depends on the incidence angle of the video picture on the slope, the distance from the recording point, the focus of the video camera and the accuracy of the reference points. For the front positions of February 25th, the absolute accuracy is below 1900m a.s.l. between ± 2 and ± 8m and above 1900m a.s.l. between ± 8 and ± 15m.

Figure 5 shows the development of the front velocities along the northern gully indicated by the line in Figure 4. The lower and upper limits of the speed indicate the error of the measurements derived from the calculated accuracy of the front positions.

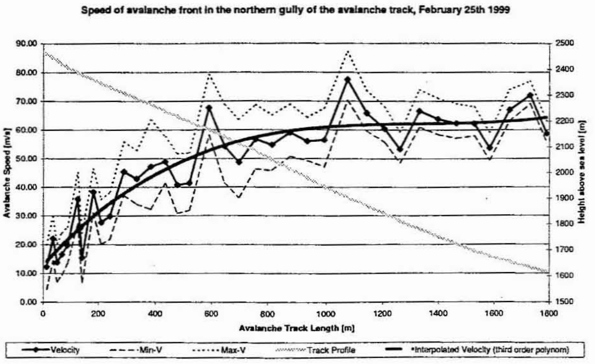

Figure 5: Front velocities derived from the front position along the longitudinal section in the northern gully shown in Figure 4. The dashed lines indicate the error range of the measurements derived of the accuracy of the front positions.

The graph shows the turbulent behaviour at the front of a large powder snow avalanche, since front velocity differences of more than 20m/s occurred within a time period of 1s. The maximum velocity of nearly 80m/s derived from the front positions occurred at the entrance of the avalanche into the northern gully, where the slope is very steep and the avalanche is channelised. A comparison to the measurements by the radars for the same time period reveals that this speed is above the speed at the maximum amplitude but corresponds well to the peak velocities of the radar measurements. Therefore, it can be interpreted that the highest speeds of the avalanche were located at the upper part of the gullies directly at the avalanche front.

In the area of the obstacles, where the terrain is flattening, the velocities at the maximum amplitude of the radar measurements are higher than the front speed derived by the locations of the front positions. The velocity of the particles at the front seemed to be slowed by the air in front of the avalanche whereas the particles behind the front still keep on moving with high speeds. The maximum speeds measured at maximum amplitude by the radar where recorded directly below the obstacles, where the previously separated flows through the two main gullies have joined completely. Unfortunately, for this time period no information from the video recordings is available, since the powder cloud covers almost completely the video image so that no reference points to orient the images could be found.

In summary, it was possible to complete with the help of both, the radar measurements and the video recordings the main characteristics of the velocities of all three avalanches. A more detailed description of the results of the combined radar and video measurements will be published in a separate paper.

5. VOLUME AND FLOW DEPTH MEASUREMENTS

The method of photogrammetry was used to measure the surface of the snow cover before and after the triggering of the avalanche. The released and deposited volumes are calculated using the difference between both states. The results of these measurements and details of the applied method are published in (Vallet et al., 2000). Therefore, only the most important findings are summarised and the deposition distribution of the February 10th avalanche shown in Figure 6 is added to the already published results.

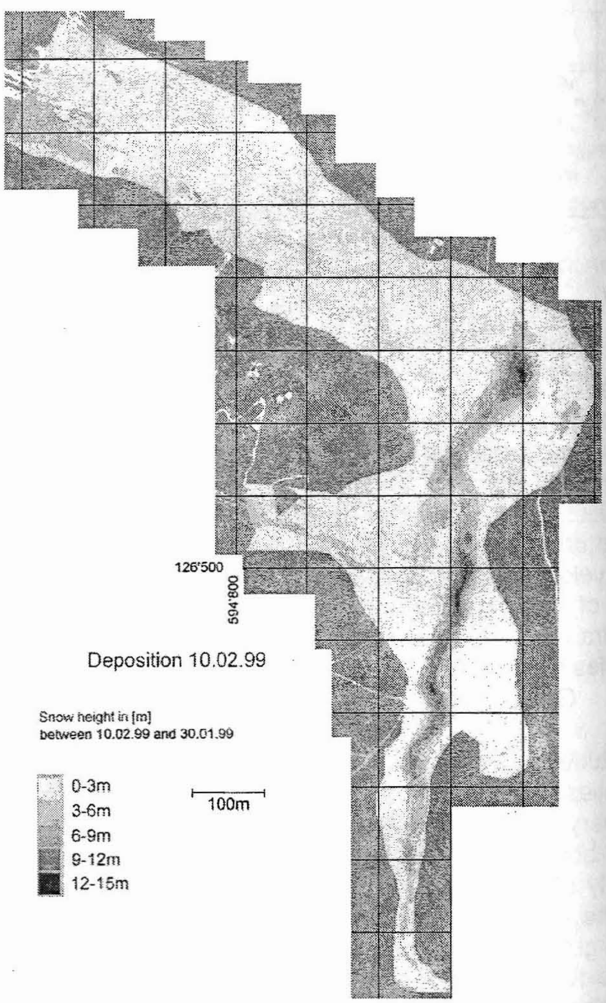

Figure 6: Deposition of the February 10th 1999 avalanche. The accuracy of the snow depth measurements are 20 – 30 cm.

The method had proved to be a very useful and reliable tool to measure large avalanche deposits. Thanks to the good contrast of the depositions, snow depth measurements with an accuracy of 20-30cm were taken using the established reference points in the terrain. Since the February 25th avalanche destroyed all existing reference points, temporary reference points were introduced. An accuracy of 60cm was achieved. In relation to the measured deposition depths of up to 16m this accuracy is sufficient. Table 1 contains the measured deposition volumes of the three avalanche events. Note that only the erosion that is visible when the avalanche came to rest is also measured. Erosion during the avalanche process that is later covered with new deposits can not be measured with this method.

Table 1: Photogrammetrically measured deposition volumes of the three main avalanche events in 1999. The February 25th avalanche eroded a part of the deposits of the February 10th avalanche.

	Event		
	01/30	02/10	02/25
Visible Deposition [m^3]	40'000	467'000	876'000
Visible Erosion [m^3]			18'000
Density [kg/m^3]	350-500	350-500	350-550

The measurements in the release area clearly demonstrated the limits of the photogrammetry. Winter conditions like stormy winds, the poor contrast of fresh snow before the avalanche triggering and the need of well distributed reference points in the release area were often limiting factors. However, it was possible to measure the fracture depth along the fracture line of all three avalanches with an accuracy of 20cm. But measurement of the released snow volume was only performed for a part of the release area of the February 10th avalanche. These measurements clearly showed that the fracture line depth is not necessarily representative for the whole area, especially when the release area consists of different slope angles and gullies (Vallet et al., 2000).

Due to the difficulties in the release area no precise information about the released volume is available. Nevertheless, using the measured depths along the fracture line, the volumetric results of the February 10th avalanche and the video recordings to define the area of the initial slab, rough estimates of the initial fracture dimensions were possible. The densities of the snow at the fracture line were measured at a few points. In Table 2 these observations and assumptions are listed.

Table 2: Rough estimates of the initial fracture dimensions.

Date	01/30	02/10	02/25
Area [m^2]	60'000	200'000	260'000
Average Depth [m]	1.40	1.20	2.00
Volume [m^3]	84'000	220'000	520'000
Density [kg/m^3]	200	220	250

In the avalanche deposits of all three avalanches densities between 350 kg/m^3 and 500 kg/m^3 were measured. Thus, considering a densification of the snow by a factor 2, the comparison of the initial volumes with the deposition volumes clearly shows the amount of entrainment of snow cover below the release area for the two events in February. The avalanche of February 25th crossed an area of 900'000 m^2 below the release area. To be able to collect the densified volume of 870'000m^3, about 1.5 m of the fresh snow cover on this area had to be collected, i.e. most of the new snow that had fallen since February 10th 1999.

This erosion of the existing snowcover is also confirmed by the FMCW-radar measurements These devices are burried at three different locations along the track and measured through the snow cover during the avalanche flow (Ammann, 1998). In Figure 7 the results of the FMCW-radar at an altitude of 1900m.a.s.l. of the February 10th avalanche is shown.

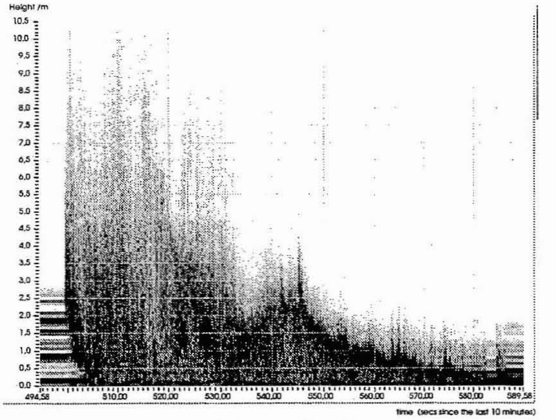

Figure 7: Snow and flow depth measurements of the FMCW radar at 1900m a.s.l. on February 10th.

The well layered snow cover at the beginning represents the existing snow cover before the avalanche reached the position of the FMCW-radar. One second after the avalanche reached the radar, particles on a height of more than 10m above the ground were measured. Within 5s after the avalanche has reached the radar all the existing snow (approximately 2.8m) was eroded. 90s after the arrival of the avalanche about 1.8m of avalanche snow were deposited above the radar.

Both the FMCW and the photogrammetric volume measurements emphasise the importance of the inclusion of the interaction of the avalanche with the existing snow cover along the whole track in the avalanche dynamics modelling. Up to now, many models that were used today in practice completely neglect the entrainment and deposition of snow along the track.

Contrary to the findings from the February 10th and 25th avalanches, the avalanche of January 30th did not entrain much snow. The most likely reason for this lack of entrainment is that on January 28th a large spontaneous avalanche had already occurred, which collected most of the existing snow along the track.

6. PRESSURE AND IMPACT MEASUREMENTS

Due to the fact that the avalanches were larger than assumed for the design of the obstacles, many problems were encountered with the measurements of pressure and impact forces. The grider mast and one section of the impact wall (see Ammann, 1998) was destroyed by a large spontaneously triggered avalanche of January 28th. This avalanche also reached the bunker on the opposite side of the slope. Therefore, no measurements were made with these two measurement devices during the three artificially triggered avalanches. On February 25th the oval-shaped 21m high pylon was destroyed, since due to the large depositions of the preceding avalanches, the dense part of the new avalanche impacted the pylon on a height that was designed only for the pressures of the powder part.

Therefore, pressure measurements were only available of the January 30th and February 10th avalanches on the oval-shaped pylon and the narrow wedge steel construction. The February 10th results of the wedge are shown in Figure 8. At 3.0m above the ground quasi-static pressure up to 500kPa persists over almost 30s, rising continually during the first 20s and then dropping slowly. Distinct impacts up to a maximum of 1200kPa clearly dominate at 3.9m. Surprisingly, significant signals last only about 13s whereas the neighboured FMCW radar recorded particles at that height over a longer time period.

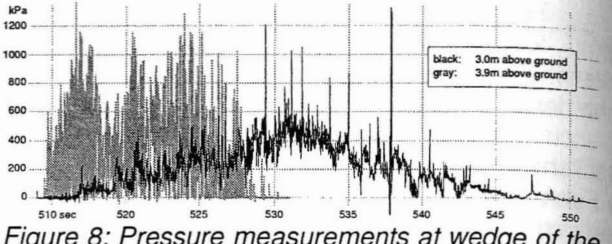

Figure 8: Pressure measurements at wedge of the February 10th avalanche.

On January 30th many of the same characteristics were found on the wedge, but they are significantly lower due to the smaller size of the avalanche. A quasi-static pressure of up to 80kPa was measured over a time period of only 5-6s. Many peaks in the 200-400kPa range were detected and only a few very strong peaks up to 1200kPa.

On January 30th significant quasi-static pressures are recorded on the pressure sensors at the pylon during 2-3s and are in an order of 4kPa at 7m and less than 1kPa at 19m. The peak pressures reached at 7m 15kPa and 5kPa at 19m. On February 10th at 19m above ground only very low pressures, rarely above 1kPa where found in the powder cloud. In Figure 9 the February 10th avalanche is shown shortly before the avalanche reached the pylon. This picture clearly shows that the powder part of the avalanche will cover the whole pylon.

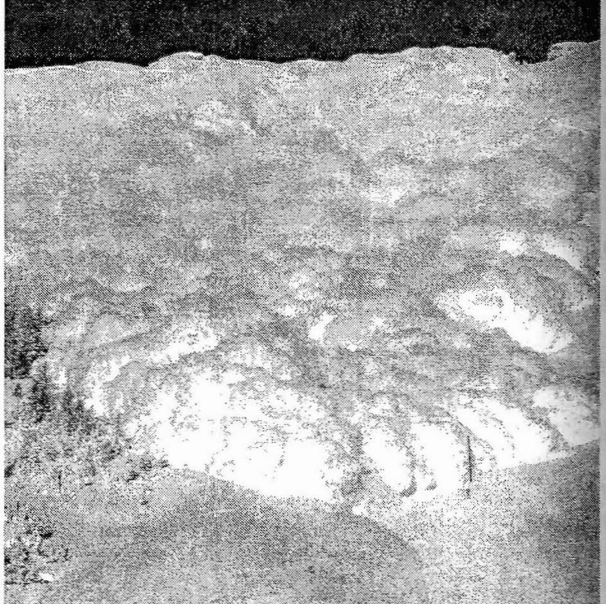

Figure 9: Avalanche shortly before the impact on the oval-shaped pylon.

From the measured front velocities and very rough density estimates, pressures of at least 5kPa were expected for these conditions. In addition, the quasi-static stagnation pressure at 7m should be even larger, but instead it is observed that pressures drop to near zero between the single impacts of up to 1200kPa. The reliability of the February 10th measurements on the pylon therefore have to be put into question. A more detailed analysis of the pressure measurements is given in (Schaer and Issler, 2000). They extended the analysis to the single particle impacts and developed a method to derive particle size and velocities. They could distinguish particles of 1cm to 50cm that impacted the load cells of the wedge on January 30th and February 10th. These findings clearly confirmed the existence of the so-called saltation layer, consisting of single snow blocks of widely different sizes. In Figure 10 a video picture of the avalanche of January 30th at a short time before the avalanche reached the bunker on the opposite side of the slope is shown. Snow blocks– directly at the front or even a little bit before the powder cloud – can be easily identified and are a further proof of the existence of a saltation layer.

Figure 10: Video-image of the January 30th avalanche taken from the bunker shortly before it reached the bunker. Flying snow blocks at the front of the avalanche are easily recognisable.

7. CONCLUSION

In the second year of operation of the experimental avalanche site Vallée de la Sionne, three large artificially triggered avalanches were measured by means of radar, video, photogrammetry and pressure sensors. The size of these avalanches can be considered as extraordinary, since at the same time many other catastrophic avalanches occurred in the European Alps causing the death of many persons. Although not all measurements could have been performed as planned due to the (1) extreme weather conditions and (2) instrument failures, a wide spectrum of data from all three was measured under save conditions.

The combination of radar and video measurement techniques gave a detailed insight into the velocities of all avalanches from the release area to the bottom of the valley in front of the bunker. To be able to measure the slowing down of the dense flowing part of future large avalanches in the southern part of the valley bottom, an additional video-camera will be installed. Furthermore it is planned to use optical speed sensors on the rebuilt oval-shaped pylon to obtain more precise velocities at the same place where the pressure measurement devices are positioned.

Photogrammetry provided good results for volume measurements in the deposition area. It stresses – confirmed by the results of the FMCW-radar – the importance of the erosion and deposition along the whole avalanche track. In order to model the deposition depths correctly, avalanche dynamics models must include these processes. However, the photogrammetry method showed clear deficiencies in the release area. To measure the release snow volume and also for the measurement of erosion and depositions along the track alternative methods have to be evaluated.

The pressure forces recorded for the February 10th avalanche quasi-static pressures of up to 500kPa and peak pressures of up to 1200kPa. The measured impacts showed – confirmed by the video recordings of the January 30th avalanche – the existence of a so-called saltation layer. Finally, since the girder mast and the impact wall were destroyed by the spontaneously released avalanche of January 28th they will not be rebuilt. However a stronger oval-shaped pylon will be rebuilt and equipped with new pressure, speed, density and flow depth measurement devices.

8. ACKNOWLEDGEMENTS

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who provided continuous local assistance and encouraged us to continue the avalanche triggering on February 25th even under these extreme conditions.

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