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# PROTECTION OF HIGH MOUNTAIN HUTS AGAINST AVALANCHE HAZARD: A CASE STUDY AT PAVÉ LAKE, FRENCH ALPS

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**ABSTRACT:** By contrast to buildings situated in valley bottoms, high mountain huts may be threatened by strenuous avalanche activity. This poses specific engineering difficulties currently overlooked in the avalanche literature. The present study gives a summary of the methodology proposed by Irstea to address the problem of avalanche hazard in the area of the Pavé lake in the French Alps, and the resulting recommendations for the location of the new hut planned and its protection. This expert appraisal work was conducted by Irstea at the request of the Fédération Française des Clubs Alpins et de Montagne (FFCAM) in charge of the management and maintenance of more than 100 mountain huts, mostly in the Alps and the Pyrenees. The Pavé lake is located at around 2800 m.a.s.l. in the Ecrins mountain range in the French Alps and is surrounded by the Pavé and Gaspard peaks. Well documented historical data on past avalanches remains extremely scarce in such a remote area essentially frequented for high mountain recreation activities. The aim of the present study is to provide an outline of the main steps of the expert appraisal work provided by Irstea.

**Keywords:** Avalanche, mountain hut, remote area, stochastic-numerical simulations, protection.

## 1. INTRODUCTION

The current Pavé lake high mountain hut is located at 2841m a.s.l. in the Ecrins mountain range close to a glacier lake, overhanging the valley of Clos des Cavales and at the foot of Gaspard peak (see an overview in Sec. 3.2, Figure 2). The Pavé lake sector is very exposed to snow avalanches but extremely weak information is available in such a remote high mountain area. Two significant avalanche events are reported in 1971 and 1979. In 1971, a big dry and cold snow avalanche came from the foot of Gaspard peak and completely destroyed the foundations of a new hut under construction (left picture on Figure 1). The construction shelter was not damaged and still serves today as a high mountain hut. In 1979, a significant avalanche occurred and blew over another hut nearby (right picture on Figure 1). Though information remains scarce, those two events suggest that avalanches coming from the release areas at the foot of the Gaspard peak can occur frequently and threaten the area where the mountain hut is currently settled. Note that the base of the current hut is about 1m below the ground and is protected by two walls (forming a bow-like structure), made of stones available on the site. Furthermore, strenuous winds result in huge snow accumulations and the hut is generally fully buried below the snow cover, thus ensuring a very good protec-

tion during winter and early spring.

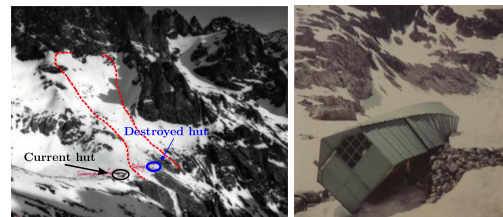


Figure 1: Avalanches of 1971 (left) and 1979 (right) (©CAF Briançon).

In 2017, the FFCAM (fédération française des club alpins et de montagne), in charge of the management and maintenance of more than 100 mountain huts (mostly in the Alps and the Pyrenees), took the decision to rebuild the hut and Irstea was asked by the FFCAM to investigate avalanche hazard in the Pavé lake sector and to propose recommendations regarding the projected hut (its location and its protection against avalanches). The present paper gives a summary of the expert appraisal work conducted by Irstea. Section 2 provides an outline of the methods used and the main steps of the study. Section 3 describes the main results in terms of release snow depth scenarios, potential release areas, avalanche hazard in terms of run-out and of impact pressure into those avalanche extensions. Section 4 gives a short summary of the main recommendations made concerning the protection strategy. Finally, the outcomes and the questions such a study may raise are discussed in Sec. 5.

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## 2. SUMMARY OF METHODS

The appraisal work conducted by Irstea was based on the main following steps: (1) predetermination of the distributions of annual maxima for both the total snow height on the ground and the height of fresh fallen snow over three days in Pavé lake area, (2) identification of potential release areas by combining field visits, topographical map analysis and an automatic objective method, (3) Monte-Carlo simulations for avalanche hazard mapping by using a propagation model based on two-dimensional center of mass equations and comparison to some avalanche events which were reported in the past (having in mind that the historical information in such a remote area is very scarce, as described in Sec. 1), (4) analysis of avalanche hazard in Pavé lake area, including the location of the currently existing hut, and identification of a potential location for the new hut, and (5) recommendations for the protection of the new hut against avalanches.

## 3. MAIN RESULTS

### 3.1. *Snow depths*

The nivo-meteorological data available around the studied area were gathered and proved to be quite abundant: 12 series of precipitation measurements over a period from 40 to 54 years, 14 snow depth series over a period from 16 to 20 years of measurements and SAFRAN-CROCUS re-analysis by mountain range, exposition and altitude zone (Durand et al. , 2009). Each of the series was analysed thanks to a classical block maxima approach (Coles , 2001). The latter consisted in retaining in each studied series the annual (winter) maxima fitting a Generalized Extreme Value (GEV) distribution on the resulting sample. The objective was to obtain two GEV distributions at an elevation of 3000m a.s.l. corresponding to two scenarios: (i) the distribution of annual maxima of snow depths on the ground, and (ii) the distribution of annual maxima of snow precipitation over 3 days.

For the maximum snow depths on the ground at 3000m a.s.l., the GEV distribution with the following parameters was assessed:  $\mu_{GEV} = 2.5\text{m}$ ,  $\xi_{GEV} = -0.15$  and  $\sigma_{GEV} = 0.5\text{m}$ . The corresponding centennial value is 4.16m. That distribution was determined from all the series available which, treated separately, gave very consistent estimates (weak spatial variability from one measurement station to another, no major influence of the slope orientation for the CROCUS re-analysis). It should be noted that snow depth measurements available at a high elevation (French NIVOSE network in particular) were gathered, thus making unnecessary an extrapolation based on elevation for that vari-

able. In contrast, the GEV distribution accounts for snow metamorphism and settling, thus explaining the negative value of the shape parameter ( $\xi_{GEV}$ ) which characterizes the fact that the distribution of extremes values is bounded.

For the 3–days snow precipitation (total snowfall of fresh snow over 3 days), the GEV law derived had the following parameters:  $\mu_{GEV} = 0.95\text{m}$ ,  $\xi_{GEV} = 0.1$  and  $\sigma_{GEV} = 0.33\text{m}$ . The corresponding centennial value is 2.88m. Again, the different sources of local measurements provided very consistent estimates, with small spatial variability from one weather station to another. However, the weather stations (snow precipitations measured in liquid water equivalent) were located at a mean elevation of 1500m a.s.l., which is much lower than the one for snow depth measurements on the ground. For the extrapolation to an elevation of 3000m a.s.l., we considered linear gradients of 0.02mm/m and 0.006mm/m for  $\mu_{GEV}$  and  $\sigma_{GEV}$ , respectively (Gaume et al. , 2013). With regard to the snow depth one, this distribution is more “optimistic” in the sense that it considers a failure of the snow cover restricted to the fresh snow precipitation. In contrast, it is worthy to note that it does not take into account the mechanical (weight of overlying layers, wind) and thermodynamic (temperature metamorphism) actions that take place the first and second days and may induce snow cover settling. This explains the positive value of the shape parameter ( $\xi_{GEV}$ ) of the GEV law, thus producing a rapid increase of the quantile with the return period.

### 3.2. *Potential release areas*

The potential release areas (PRAs) were determined by using and combining the following approaches: a field visit to the site of Pavé lake, the analysis of topographical maps (before and after the field visit), and the use of the objective method earlier proposed by Maggioni and Gruber (2003). The latter was based on an ensemble of topographical criteria and applied, in the present study, to an elevation digital model with a 10m resolution. Four main PRAs were identified, as depicted in Figure 2: (1) the Pavé pass PRA, made of a large zone oriented from East to South and of mean slope 30°, and two other zones of mean slope around 35°–40° (a surface of ~ 15ha in total), (2) the 1971 PRA oriented from South to South-West and of mean slope 30° (~ 6ha), (3) the face-to-lake PRA, oriented from South-West to East and of mean slope 35° (~ 6ha), and (4) the Pointe Emma PRA, oriented East, of mean slope 30°–35° (~ 5ha).

The 1971 PRA (zone 2 on Figure 2) was the active release area during the avalanche which destroyed the hut being built in 1971 (see Sec. 1).

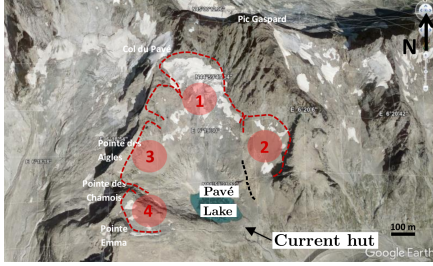


Figure 2: The four PRAs identified in the Pavé lake area (red-colored dashed lines). The black-colored dashed line roughly depicts the moraine south of PRA 2 (see text for explanation).

### 3.3. Avalanche hazard: extensions

The avalanche hazard in term of extensions was determined with the help of a two-dimensional center of mass model developed at Irstea (2DCM) in order to predict the avalanche propagation of dense flows. The main input parameters of the 2DCM model are the release depth  $h$ , and the rheological parameters  $\mu_0$  and  $\xi$ , on the basis of the Voellmy rheology (Voellmy, 1955) for flowing snow. A digital elevation model of Pavé lake area, with a resolution of 5m, was used for the numerical simulations.

For each PRA defined in the previous subsection, a number of release points was distributed uniformly on the PRA considered: 12 release points for the Pavé pass PRA, 6 release points for the 1971 PRA, 7 release points for the face-to-lake PRA and 3 release points for the Pointe Emma PRA. For each of the release points, 10 000 simulations were done by choosing randomly the three input parameters  $h$ ,  $\mu_0$  and  $\xi$  into probability distributions. This probabilistic method (of Monte-Carlo type) is now well-established to quantify avalanche hazard (Meunier and Ancey, 2004; Eckert et al., 2008) and allows to simulate an ensemble of possible scenarios. The statistical distributions used were all GEV laws.

The GEV laws and their parameters for snow depth inputs were already discussed in Sec. 3.1. The use of GEV laws for the rheological parameters stems from an arbitrary choice mostly governed by a rapid and efficient calculation process (the GEV laws are easy to inverse in particular). For the GEV distribution for the turbulent friction coefficient ( $\xi$ ), a mean value  $\mu_{GEV}$  equal to  $1000\text{m s}^{-2}$  and a low variability ( $\sigma_{GEV} = 50\text{m s}^{-2}$ ;  $\xi_{GEV} = -0.05$ ) were chosen. That mean value is justified because of the presence of quite smooth and open slopes in the Pavé lake sector. Concerning the GEV distribution for the dry friction parameter  $\mu_0$ , we chose to consider a widespread distribution with the emphasis on small values of  $\mu_0$  (the GEV parameters for the inverse of  $1/\mu_0$  were  $\mu_{GEV} = 3.3$ ,  $\xi_{GEV} = -0.05$  and  $\sigma_{GEV} = 0.8$ ). This choice was made to simulate a wide spectrum of snow types from a very fresh and cold snow ( $\mu_0 = 0.11$ ) to a heavier and much more

frictional snow ( $\mu_0 = 0.85$ ) without lubrication taking place (it is now well-established that beyond a certain amount of liquid water content, the effective friction drops down (Naaïm et al., 2013)), by giving more weight to the small values of  $\mu_0$ . Small values of  $\mu_0$  (very cold and dry snow) are known to produce catastrophic and unforeseen avalanche events.

A first output of the numerical simulations are spatial maps in terms of avalanche extension, with an indicator of the annual likelihood that an avalanche follows one single trajectory. The latter indicator is roughly defined as the product of the annual release probability and the number of passages, divided by the total number of avalanches (equal to the number of simulations for one single release point, namely 10 000, multiplied by the number of release points). For the present study, the release probability was fixed at 0.3/path/year, which is the average value estimated on the French Alps based on all the historical information available (Eckert, 2008).

Figure 3 shows the results of numerical simulation campaigns for two scenarios in terms of input release depth  $h$  in the PRAs (Sec. 3.2), considering the total snow depth on the ground and the fresh snow depth over 3 days (Sec. 3.1). The color levels shown on Figure 3 directly result from the indicator of avalanche passage likelihood discussed just above: the red color corresponds to high frequency of passage, the yellow color to medium frequency and the blue color to small frequency. Those extension spatial maps show that the current mountain hut is concerned by snow avalanches coming from the 1971 PRA, regardless of the input release depth scenario considered. From that first analysis, a potentially safer zone is identified in the sector of the mountain ridge leading to Pointe Emma (Figure 3).

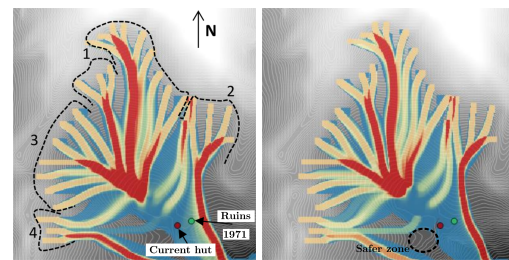


Figure 3: Spatial map of avalanche extensions for two release depth scenarios: total snow depth on the ground (left) and 3-days fresh snow depth (right). The red color corresponds to high frequency of avalanche passage, the yellow color to medium frequency and the blue color to small frequency (see text for explanation). The red and green circles indicate respectively the locations of the current hut and of the hut destroyed during its construction in 1971 by an avalanche.

The avalanche hazard was then investigated in more details by considering each PRA separately (results not shown). The main results are now summarized. It can briefly be said that the Pavé pass PRA (zone 1 on Figure 2) and the face-to-

lake PRA (zone 2 on Figure 2) are not expected to produce dense flows able to reach the current mountain hut, though some extreme avalanches may be able to travel a distance equal to about  $2/3$  of the total length of the Pavé lake. Most of the avalanches coming from the 1971 PRA have the following trajectory: they travel through the slopes oriented South down the valley of Clos des Cavales and do not impact the current hut (trajectories in red color in the left bottom corner of each picture shown on Figure 3). By contrast, some of the dense flows are able, more rarely, to overtop a moraine (see black-colored dashed line on Figure 2) with a more straight-lined trajectory toward the Pavé lake and the current hut. The trajectory followed by the avalanche in 1971 (Figure 1) is clearly identified by the present simulations based on the 2DCM model. Under dry and cold snow conditions (small  $\mu_0$ ), the numerical simulations confirm that the hut which was under construction in 1971 was exposed to snow avalanches. The current hut is also concerned by potential avalanches. A neighbour's hut was blown over in 1979 (see Figure 1): that avalanche of 1979 belonged to the family of avalanches that can threaten the current hut.

Finally, the Pointe Emma PRA merits specific attention because of a quite complicated behaviour. The numerical simulations based on the 2DCM model show that at least three different families of avalanches in terms of run-out trajectories can be distinguished. First, some of the avalanches travel down the Pavé lake following a run-out trajectory similar to the trajectory followed by some avalanches coming from the face-to-lake PRA. Second, a family of avalanches reach the lake by travelling down a canyon. Third, a family of avalanches flow down the valley of Clos des Cavales on the right side of the ridge. Considering those three families of avalanches, a safer zone may appear at the foot of the ridge for the location of the new hut. However, it is not excluded that large avalanches of dry and cold snow starting from the Pointe Emma PRA do not follow the canyon, produce secondary releases on the ridge (it is now well-established that secondary releases can strongly govern the dynamics of snow avalanches (Köhler et al., 2016)) and thus threaten the potential safer zone identified on Figure 3. In order to further investigate this hypothesis, an additional series of numerical simulations were performed by considering other release points below the Pointe Emma PRA, as depicted in Figure 4 (left panel). While some avalanches travel down the lake through the canyon, most of the avalanches are able to stay on the ridge and reach the zone that was identified as a safer zone, before either stopping in that zone or travelling down the valley of Clos des Cavales. Those results demonstrate here the richness of information that can be obtained

from the stochastic-numerical simulations based on the 2DCM model when historical information is not available.

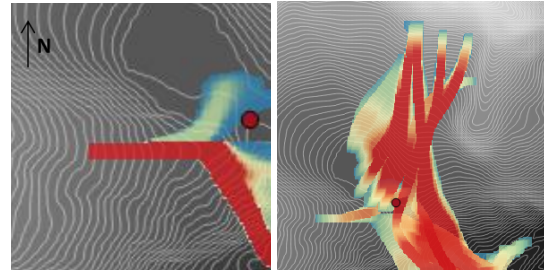


Figure 4: Spatial map of avalanche extensions for a 3-days fresh snow depth scenario, considering a secondary release point on the Pointe Emma ridge (left). Maximum impact pressure distribution of avalanches starting from the secondary release point on the Pointe Emma ridge and from the 1971 PRA (right). On both maps, the red circle indicates the location of the current hut. See caption of Figure 3 for the meaning of colors.

### 3.4. Avalanche hazard: impact pressures

The maximum impact pressure generated at each position by the ensemble of avalanches simulated can be calculated. It is possible to draw up a map showing the spatial distribution of those maximum pressures, as drawn on Figure 4 for the 3-days fresh snow scenario (right panel). The impact pressure of the “free” flow (undisturbed flow) was calculated as the sum of two contributions:  $P = 0.5\rho u^2 + \rho gh$ , where  $g = 9.81\text{m s}^{-2}$  holds for gravity acceleration and  $\rho$  is the mean density of the dense avalanche ( $\rho = 250\text{kg m}^{-3}$ ). The first term corresponds to the inertial contribution (proportional to the square of maximum velocity) and the second term accounts for the hydrostatic force (associated with the flow thickness,  $h$ , assumed to be equal to the release depth in the center of mass framework). The results show that the current hut is concerned by avalanches of low frequency of occurrence but of potentially high impact pressure of about 200kPa. The zone at the foot of the Pointe Emma is concerned by some avalanches too but of smaller potential impact pressure not exceeding 100kPa.

## 4. SUMMARY OF MAIN RECOMMENDATIONS

Based on the analysis of avalanche hazard in the Pavé lake sector in terms of avalanche extensions and of related maximum impact pressures within the avalanche extensions, it was recommended to remove the current mountain hut and build the new projected hut in a safer zone, at the foot of Pointe Emma ridge, as displayed on Figure 5. However, because of the significant level of maximum impact pressure generated by potential avalanches reaching that area (100kPa), a number of recommenda-

tions were made in terms of avalanche protection which can be shortly summarized as follow: construction of a bow-like wall to face dense flows that potentially come from the Pointe Emma, excavation to protect the base of the hut, reinforcement of the roof and safety measures against the potential aerosols produced by the 1971 PRA.

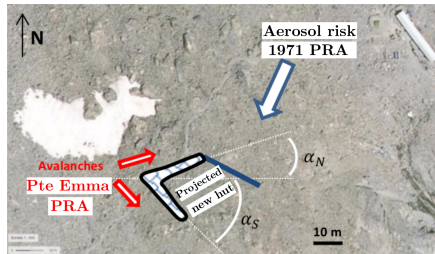


Figure 5: Sketch of the projected protection system for the new hut of Pavé lake.

## 5. CONCLUSION AND DISCUSSION

The present paper concerned a specific case-study related to the quantification of avalanche hazard in a high mountain area and protection of a new projected hut in that remote area. In a complementary manner to traditional yet essential approaches (use of available field measurements—snow and weather stations in the present study, field visit of the site, topographical maps analysis, collection of testimonies, archive material analysis, etc.), a number of stochastic-numerical simulations were conducted to quantify snow depth distributions, and avalanche hazard in terms of both extensions and impact pressures. In addition to available measured data from stations close to the area (snow water equivalent, fresh snow precipitations measured at high altitude stations), the use of SAFRAN-CROCUS re-analysis data allowed to derive consistent snow depth release scenarios for the high mountain remote area of interest. In a context of very scarce information about avalanche activity in terms of run-out distances, the stochastic-numerical simulations based on the center of mass model gave quick and valuable information to estimate avalanche hazard. It is worthy to note the method was found to be efficient at retrieving the few events documented (two events in 1971 and 1979). However, some important assumptions made should be kept in mind. Future work should pay attention to the distributions chosen for the rheological parameters  $\xi$  and  $\mu_0$ . In the present study, choosing a narrow GEV distribution for  $\xi$  was reasonable but  $\xi$  may exhibit significant spatial variability in other case-studies. In want of any knowledge about the distribution of  $\mu_0$  for the present case-study, choosing a GEV distribution was mainly justified by the choice of giving more weight to the small values

of  $\mu_0$ —which are known to produce catastrophic and unexpected avalanches (to be on the safe side). Future work will address a calibration of those distributions on well-documented sites as well as a comparison to other families of distributions. Moreover, future studies should address the detailed evaluation of those stochastic-numerical simulations based on the center of mass model (used here), in particular by comparing them to previous studies based on more sophisticated (yet more time-consuming) 1D depth-averaged models for avalanche propagation (Eckert et al. , 2010).

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