"IN-SITU" MEASUREMENTS TO TEST CROCUSMEPRAPC TOOL.

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Abstract : Since the 1999/2000 winter season, the Snow Research Centre of Meteo-France (CEN) has carried out various snow measurements in a new observation site. This site named "Col de La Botte" is located near the Chamrousse Olympic ski resort in the Belledonne massif.

The study slopes varied between 35 to 40 degrees inclination, with north and west aspects for a main elevation of 2150m.

Snow measurements like :

- complete and detailed snow pits (ram resistance, density, liquid water content, stratigraphy...)
- stability tests like rutschblock, shovel tests

have been made with a frequency depending on the snow stability situation :

Similar measurements were also conducted when avalanches were triggered by skiers.

For us, the both main objectives of these measurements are :

- better knowledge about the stability tests (carrying out in deep slopes and results interpretations)
- validation of the stability analysis made by the Mepra expert system.

Using CrocusMepraPC tool, some comparisons have been made between Mepra results and snowfield measurements (snow pack profile, Mepra avalanche risks, unstable levels..). To take into account the spatial variability of the snow pack, CrocusMepraPC is also used to simulate the field snow pits with modifications in the critical weak layers and in the overlying layer (mechanical properties, depth...).

Further Mepra snow stability consequences have been discussed.

Keywords : snow stability, avalanche forecasting , computer tool, snow stratigraphy

1. Introduction

Numerous softwares have been developed for avalanche forecasting. CrocusMepraPC (Giraud et al., 2002) is a new software for local simulations of the snow cover. It is a product of SafranCrocusMepra chain, developed by the CEN (Centre d'Etudes de la Neige). Mepra, based on an expert system, is the part of the model which estimates the avalanche risk. It has been evaluated with the context of regional avalanche forecast (Giraud et al., 1998). Our aim is to evaluate Mepra analysis of the accidental avalanche hazard on local measured profiles. Comparisons between Mepra stability analysis and slope measurements as well as stability tests or observed snow profiles after avalanche release are detailed in the following.

2. The site and the measurements

2.1 Location

The site named "La Botte" is located near Grenoble in French Alps in Belledonne massif. It is close to the Chamrousse ski resort.

The site choice of La Botte fulfils our initial requirements :

CEN closeness. Around 1 hour is needed to reach the measurements site, by car, ski lift and finally ski and walk.

Good collaboration with snow patrollers.

Undisturbed Site. The site is not usually skied, due to the poor ski interest and the access by walk

Consistent nivo-meteorological device is close to the site; facilitating the knowledge of the snow pack evolution on our measurement slopes. This device is made up of :

the automatically Nivose station (Croix de Chamrousse) supplying hourly measurements (Tair, U%, wind speed, snow depth),

the Chamrousse nivo-meteorological measurements site carrying out two daily human meteorological and snow observations,

the snow pit measurements place of the Chamrousse ski resort: Weekly snow pit is performed by Ski patrollers.

The elevation range of La Botte slopes is , 2050 to 2250 m, usual range for mountain ski.

Last requirement was the secure access on the slopes. For that, it was easy to fit out the top of slopes with anchoring. In case of slab instability, a rope is used to access to the measurement sites.

2.2 La Botte slopes

Six possible slopes were first selected, but finally only two of them have been used; the first one with North aspect and the other one with West aspect.

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Topographic parameters of these both slopes are:
for the North slope : elevation, top 2210m, bottom 2130 m; aspect 20°; steady slope angle 35°; ground characteristics : short grass, rhododendrons and little stones.
for the West slope : elevation, top 2180m, bottom 2080 m; aspect 275°; steady slope angle 33°; ground characteristics : short grass and little stones.

Both slopes are remarkable by their spatial uniformities : no important rocks, no breaking slope.

2.3 Measurements

During the last three winter seasons, we performed detailed snow pits most often associated with stability tests like rutshblocks and shovel tests. A particular attention was focussed on the characteristics of the weak and slab layers. Grain types, density, hardness, shear strength (measured with a rotary shear vane) were meticulously described.

The first objective consisted in obtaining an expertise in stability tests, rather unknown in France, and testing our ability to carry out such measurements on steep slopes. During the first season we tried to perform weekly measurements apart from the stability of the snow pack.

During the following winters, we focussed on unstable snow slab periods. Unfortunately, such conditions were rare during these last winters and that is how on this site our documentation is not today very consistent.

Although, we collected twenty detailed measurements, in case of stable as well as unstable snow slab situations on the Botte slopes.
Results are as follows :
Rutshblock scores

	Slope North	Slope West	Others slopes
Rutshblock event	8	6	2
Score 1 to 3	4	3	1
Score 4 to 5	1	2	0
Score 6 to 7	3	1	1

2.4 Avalanches reports

Other measurements from avalanche reports of the CEN in the French Alps were also used within the framework of this study. These measurements consisted of detailed snow pits performed at the failure of slab avalanches triggered by skiers.

3. CrocusMepraPC Model

CrocusMepraPC software (Giraud et al, 2002) is a tool running on a PC. This software simulates the energy, mass and morphological evolution of a local snow profile using the Crocus French snow model (Brun et al, 1992), analyses the mechanical stability of the simulated snow profile and deduces an accidental and natural avalanche risks with the Mepra expert system (Giraud et al, 1992).
The main objectives of this paper are to compare snow measurements made near the "Col de la Botte" site or after avalanche releases and the Mepra stability analysis. For a better understanding, some details about snow profile measurements, Crocus/Mepra snow profile and also Mepra accidental stability and risk analysis are needed.

3.1 Differences between snow pit measurements and Crocus profile

To make a CrocusMepraPC run using snow pit measurements, some modifications concerning the measures are needed :

- Snow observers use the basic "International Classification for Seasonal Snow on the Ground" (Colbeck S and al, 1990) to describe the grain types. The Crocus French snow model has introduced a formalism to describe snow as a function of continuous parameters : dendricity, sphericity, grain size and history. In CrocusMepraPC software, Crocus formalism is used to input the grain types of the initial snow profile. Two tables (fig 1 and 2) allow the local avalanche forecaster to adapt the observed grain types.

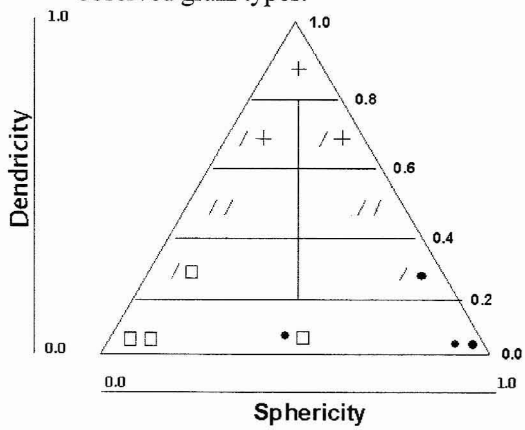

Figure 1 : Table of correspondence between Crocus dendritic grains and grain types function of dendricity and sphericity

Spher. \ Hist.	0	1		2		3
	□□	d < 0.5	□□	∀d	○□	○□
		0.5 < d < 1.0	□∧			
		d > 1.0	∧∧			
0.2						
	●□	d < 0.5	●□	∀d	○□	○□
		0.5 < d < 1.0	□∧			
		d > 1.0	∧∧			
0.5						
	●□	d < 0.5	●□	d < 0.5	●○	○∧
		0.5 < d < 1.0	●□	0.5 < d < 1.0	○○	
		d > 1.0	∧○	d > 1.0	○○	
0.8						
	●●	d < 0.5	●●	d < 0.5	●○	○∧
		0.5 < d < 1.0	●●	0.5 < d < 1.0	○○	
		d > 1.0	∧○	d > 1.0	○○	

Figure 2 : Table of correspondence between Crocus non dendritic grains and grain types function of sphericity, historic and size (d)

Mepra snow profile

Before analysing the snow profile in term of natural and accidental mechanical stability, the Mepra expert system deduces from each layer of the Crocus snow profile additional mechanical characteristics like ram resistance, shear strength, snow shear stress (τ_n) and skier shear stress (τ_s).Using experimental laws, the shear strength is estimated depending on the grain type (dendricity, sphericty, historic) and size, the density and the LWC of each layer. The snow shear stress (is calculated function of the layering, the density of each layer and the slope angle. For the stress due to the skier, some hypothesis have been made :

- the additional shear stress inside the snow pack follows a Boussinesq or Westergaard law like in mechanical behaviour of soils.
- the estimation of the skier load value depends on some parameters : additional charge due to the skier loading or jumping on the snow, load distribution on the skis, interactions between snow and skis, layering of the snow pack....Using information of ROSSIGNOL company, we estimate that the skier weight (80 kg) is distributed on half of the skis. An analytical estimation of τ_s, function of the snow depth , has been made on a snow pack (density = 300kg) with a 1.5 coefficient due to the skier loading or jumping (Föhn.and al, 1992 and Schweizer and al, 1995) (figure n° 3).

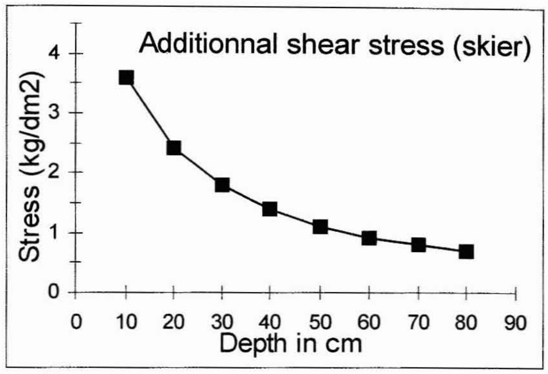

Fig 3 : Skier Shear stress (τ_s)

To take into account the snow pack layering, a β expert coefficient has been created. In the snow pack, the absorption and also the propagation of the skier stress depends on the state of each layer. For example, hard layer absorbs and propagates on the side the stress but also the hardness can be source of vibration and short peak of stress. This β expert coefficient has been estimated with a value from 0.5 (refreeze snow) to 1.2 (new dry snow).

Mepra accidental risk analysis

The expert system interprets the snow pack structure to detect the possible release of a dry slab avalanche by a skier. It is considered that slab avalanches start with a shear fracture or a collapse in a weak layer or interface underlying a relatively cohesive slab (Schweizer, 1993, Jamieson and Johnston, 1993).

Then in a first step, Mepra calculates, for all the layers of the simulated snow pack's upper meter, a stability index integrating human triggering (Fohn, 1987a, Giraud, 1995), based on a simple rankine equilibrium:

$$S' = \frac{C}{\tau_n + \beta * \tau_s}$$

or

$$S' = \frac{\textit{shear strength}}{\textit{snow shear stress} + \beta * \textit{skier shear stress}}$$

High or moderate mechanical unstable levels are detected if S' value is less than 1.5 or between 1.5 and 2.5 in faceted crystals, depth hoar or new snow layers.

These unstable levels will become high or moderate weak layers if part of the overlaying snow can be considered as a relatively cohesive slab. To do that, the expert system analyses the overlaying layers to detect a snow slab, function of grain type (rounded grains and/or fragmented particles), size and shear strength (more than 1.5).

Depending on the S' index value and the presence of an overlaying cohesive slab, an accidental avalanche risk is deduced on a 4 levels scale (very low, low, moderate, high).

4. Results

The method we used for checking Mepra analysis varied according to the data source.

Part of the measurements were done after an avalanche have occurred. It was therefore possible to compare the level of the simulated accidental risk (high or moderate) to the conditions of the avalanche release (one isolated skier or a group of skiers) and the weak layer detected by Mepra to the observed one. The main drawback is that we only checked unstable conditions.

The second source of data was La Botte measurements. Stability tests are acknowledged to be a useful indicator of slope stability. They provide a depth of failure and a score which can be related to a level of instability. So we tried to check the depth of failure against the depth of the weak layer detected by Mepra and the score test against the estimated level of risk.

The measurements were not enough numerous for a statistically significant comparison. Moreover Mepra model easily provides a justification of the simulated risk. The following results are a list of examples which illustrate Mepra analysis of the accidental risk for various typical snow profiles. They show the interest and the limits of the use of this model for a stability estimation on a slope and point out some possible improvements. In the figures, scores of the stability tests are noted: R for a Rutshblock test, Sh for a shovel or compression test. The number is either the score of the Rutschblock (Fohn, 1987b) or the score of the shovel tests : 0 : *very easy* (a failure occurred while isolating the column), 1 to 3: *easy*, *moderate* or *hard* according to the classical descriptions of these test (Jamieson, 1999a).

4.1 La Botte measurements

- Weak layers sometimes consist of graupel. This type of grain is unknown by the Crocus model. We replaced graupel layers with depth hoar layers, same grain size, same density. Grains of graupel are large grains with few contacts between them, so Mepra reasonably estimates the shear strength.

- The 2 snowpits shown in fig 4 were realized the same day, after a quiet snowfall. Their characteristics are similar: typical of a soft slab profile in the upper layers. The newly fallen snow overlays a weak layer of graupel, fallen in the start of the snowfall. Stability tests acknowledge these snowpacks as unstable, Mepra analysis of the accidental avalanche risk varies from low to high. Unstable levels are detected in the 2 profiles but accidental risk also needs the presence of a slab layer. Mepra criteria for a slab layer is a threshold of 1.5 on the shear strength. In figure 4a, all the estimated shear strength for the upper layers are under the threshold, in figure 4b, one of them is just above the threshold. That shows the limit of Mepra analysis of soft slab avalanche risk. It points out a lack of knowledge in the characterisation of soft slab layers in term of ability to propagate a failure.

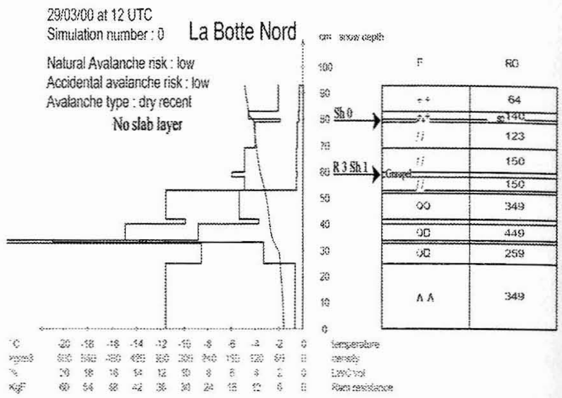

Figure 4a: recent snow overlaying graupel.

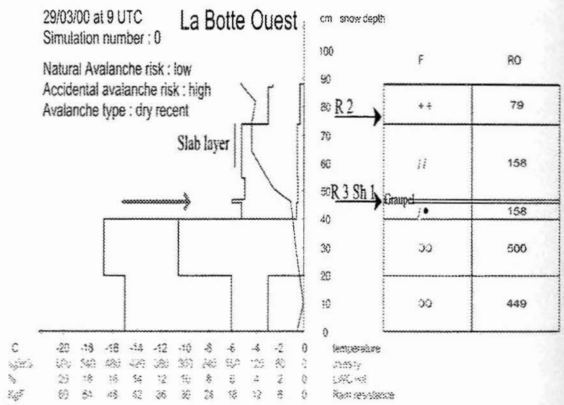

Figure 4b: soft slab layer detected in recent snow.

- For the profile shown in figure 5, the Rutschblock score is 4, moderate instability, while a low risk is analysed by Mepra. In that case, the superficial melt-freeze crust ensure the global stability of the snowpack. The relative thickness of the crust allows the stress due to the skier to reach the weak layer of faceted crystal and to release the isolated block. Mepra criteria for the stabilizing effect of an existing melt-freeze crust over a weak layer is its thickness, at least 4 cm.

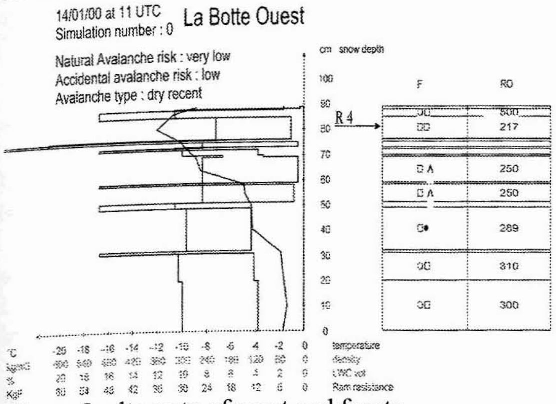

Figure 5: alternate of crust and facets.

- Figures 6a and 6b illustrate the analysis process when exist several level of instability. Stability tests show several weak layers with level of failure *easy* to *moderate*. Mepra always holds back the closest to the surface weak layer, for each level of instability (moderate or high). In figure 6a, stability tests detect a more buried layer, it was in fact the weakest one.

Figure 6b, accidental risk is moderate while one of the Rutschblock test is 3 in a more buried layer. Moreover this layer was not the weakest one but it was overlaid by a thin crust. The thin crust probably concentrates the stress in the underlying faceted crystals (Jamieson, 1999b). Effect of crust on stability is difficult to interpret. Presence of a thin crust could increase the accidental risk while a thicker crust tends to stabilize the snowpack. Mepra only takes into account the second effect.

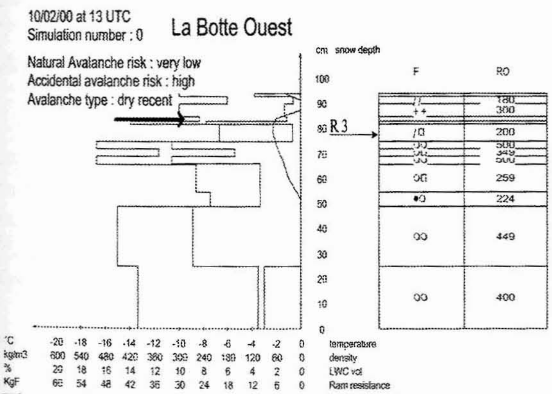

Figure 6a: presence of several buried weak layers.

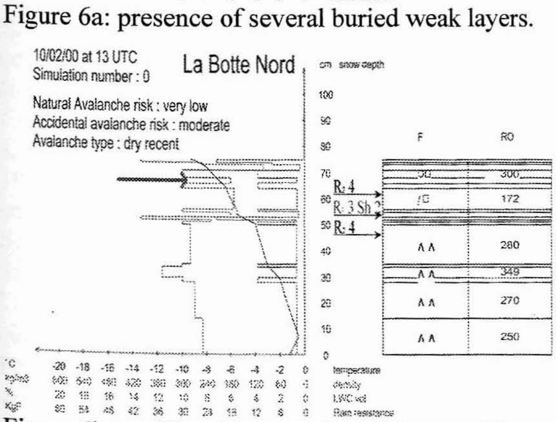

Figure 6b: profile with several weak layers of facets.

4.2 Avalanches

In most cases, avalanches were triggered by one or several skiers. Measurements were done most often the day after the triggered avalanche. They were located near the failure of the avalanche but sometimes on a close slope with similar conditions. We compared the detection of the weak layer with the one noticed in the avalanche report and the level of accidental risk with the type of triggering. For instance, if the avalanche was triggered by the first skier or after several tracks, an isolated or a group of skiers, ... Mepra analysis was usually in good agreement with the report. The weak layer was well detected and accidental avalanche risk was estimated high. The following results show typical avalanche snow profiles.

- The fig 7 illustrates a classical case of hard slab avalanche where the slab consists of dense rounded grains, probably accumulated by wind, and the weak layer of depth hoar and faceted crystals.

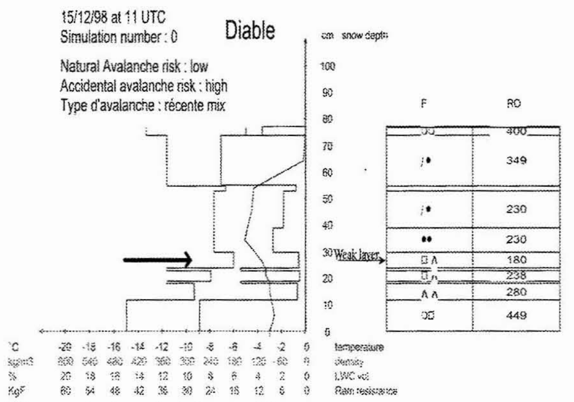

Figure 7: hard slab profile.

- The next example is rather a soft slab avalanche, triggered by a skier in a forest. The weak layer consists of a thick layer of depth hoar, with a low density (figure 8). The very thin crust overlaying depth hoar is not able to stabilize the snow pack, it should be an increasing factor for the avalanche hazard. Mepra analyses correctly the accidental risk.

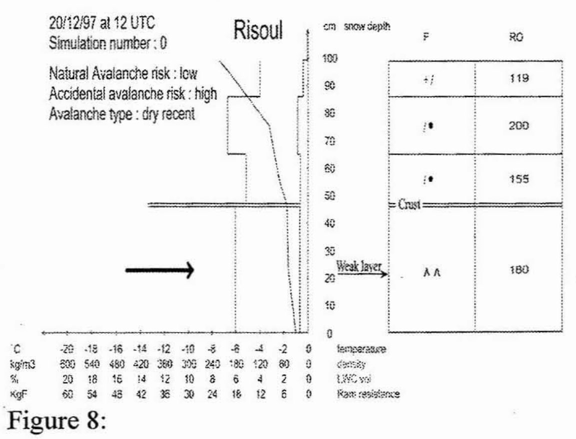

Figure 8:

- Another classical slab profile is shown in figure 9. The slab consists of a layer of rather dense rounded grains, topped by 15 cm of newly fallen snow, based on depth hoar. The difference with the previous cases is the thickness of the weak layer, about 1 cm. just under a thin crust of ice. Compression test produced easy failures in this layer. Mepra as well analyzed a high unstable level.

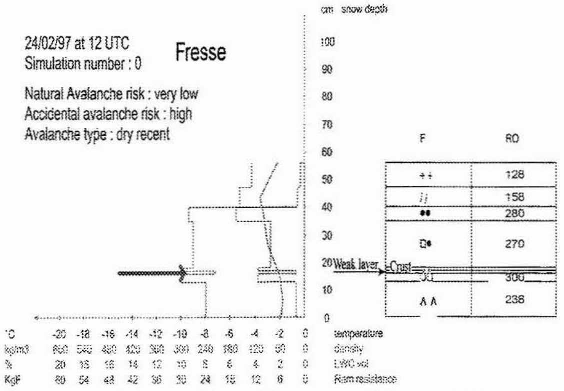

Figure 9: slab profile with a very thin weak layer.

- Figure 10 shows again a slab profile with a very thin weak layer. In that case, the weakness is due to buried surface hoar. Crocus does not recognize surface hoar, so the entered grain type is depth hoar, which allows Mepra to correctly estimate the shear strength.

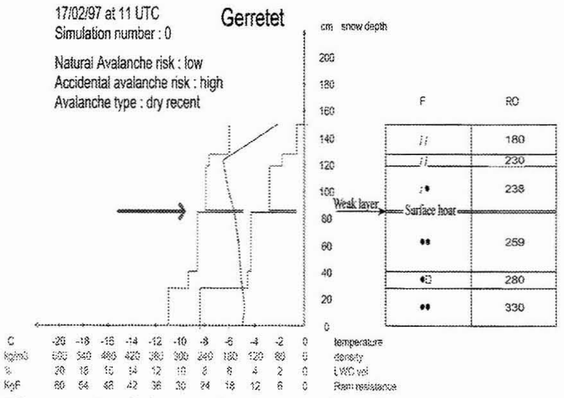

Figure 10: slab overlaying surface hoar.

- The next avalanche was triggered after several skiers have crossed the slope. The weak layer of graupel is buried under 80 cm of newly fallen snow (figure 11). At such depth, the additional shear stress due to a skier is low. A moderate unstable level is detected and leads to a moderate accidental risk. Unfortunately a very large avalanche was triggered due to the presence of depth hoar at the basement of the snow pack and the lie of the slope.

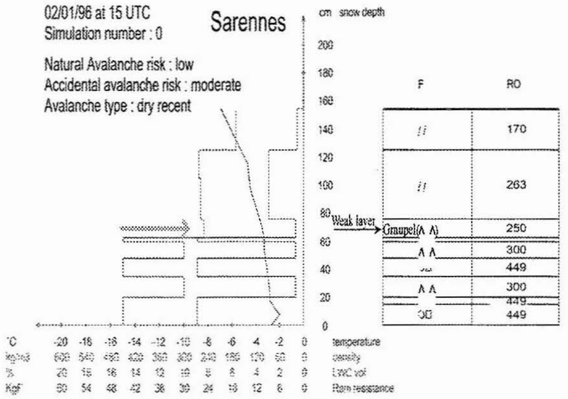

Figure 11: thick slab avalanche.

- The two last figures illustrate weak layers of recent snow. Figure 12 is a soft slab avalanche profile where the weak layer consists of partly decomposed particles. In figure 13, the snow profile is also a soft slab profile with newly fallen snow in the weak layer and a lightly stiffer slab. The main difference in Mepra analysis is that in the second case the accidental risk is due to a high natural avalanche risk . Mepra always sets the level of the accidental risk at least equal to the natural risk level. Therefore, we do not know if a slab profile was detected, which is more hazardous for a skier.

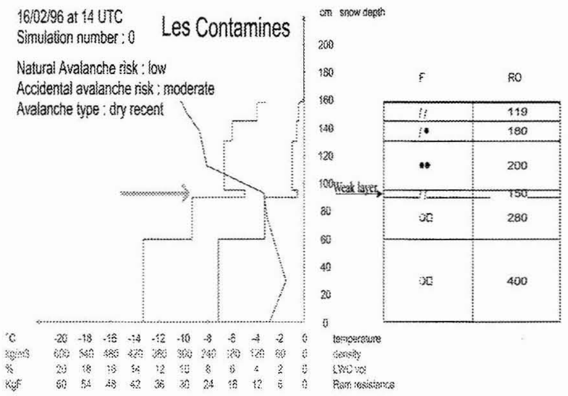

Figure 12: soft slab profile.

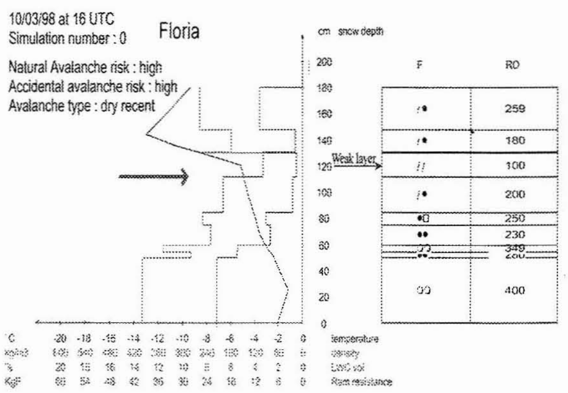

Figure 13: additional natural avalanche risk.

5. Conclusion

Results suggest possible improvements in Mepra analysis system.

✓ When exist several accidental unstable layers, Mepra might not only indicate the less buried but at least the weakest too.

✓ Thin crust overlying a weak layer is often observed in avalanche snow profile. The resulting increase of the stress in the weak layer might take into account.

✓ The link between accidental and natural risk is not adapted to a local evaluation of the stability. Mepra should give the justification of the accidental risk analysis however high the natural risk is.

✓ Further studies are needed on the characterisation of soft slab layer stiffness.

In addition, some improvements of the software are needed for a better use by local avalanche forecasters. In order to make easier the data input, it is necessary to develop an automatic conversion of the observed data into Crocus format. This requires to include the grain types unknown by Crocus, as well as surface hoar and graupel. Another simple improvement should be to take into account the shear strength measurements when they exist instead of the value estimated by Mepra.

The results have shown that CrocusMepraPC could be an interesting tool for analysing the stability of observed snow profiles. Usable in analyse or forecast mode, it could be helpful for slope avalanche hazard evaluation within the framework of a local avalanche hazard warning service.

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