# EVALUATION AND IMPROVEMENT OF SNOW STABILITY TESTS BASED ON MEASUREMENTS ASSOCIATED WITH REAL AVALANCHES

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ABSTRACT: A number of snow stability tests (Rutschblock, CT, ECT, PST) have been in use for long. However, some dramatic cases have shown their limitations as soon as they started being popularized (Munter). This is why we initially ascribed them (since 2006) little predictive value, as for classic stratigraphic profiles. Nevertheless, by systematically practicing them during avalanche accidents judicial investigations since 2018, A. Duclos observed constants that seemed empirically robust, among the hundreds of tests (more or less formal before 2020) practiced elsewhere in the context of operational missions for roads avalanche safety. This is why we have developed a methodology for conducting, recording, and sharing snow stability tests, gathered in a unique online database, now rich with over 700 tests, all conducted according to the same protocol. Among them, more than 50 are associated with real avalanches, dated, geolocated, and described. The tests have sometimes been conducted in the immediate vicinity of the avalanche starting zone (e.g., crown rupture) immediately after its occurrence (e.g., for accidental avalanche triggered by observers). More often, they could only be carried out one day or two after the avalanche, but always as close as possible to the starting zone. Sometimes they were also conducted before the feared avalanche release. These observations and measurements are analyzed taking into account this diversity of situations. They are compared to the exhaustive population of tests not associated with an avalanche. The initial results have allowed determining PST initiation length thresholds, and crack and column behaviors, typical of situations where an avalanche is very likely to occur, provided that other parameters as topography, snowpack continuity... etc., are also favorable. In some well-identified situations, they also show that ECTs deliver more significant results than PSTs. However, CTs are mainly used to identify and locate the presence of weak layer(s), without reliable predictive value. Continued measurements by the same operators led to protocol evolution, notably through a relevant ECTs integration. The objective remains to best combine terrain constraints (feasible in alpine conditions by two experienced mountaineers within a reasonable time lapse) and a result as reliable as possible derived from the combination of several tests.

KEYWORDS: Snow stability tests, PST critical initiation cuts, significant triggering probability, snowpack measurements, avalanche prediction.

## 1. INTRODUCTION

The assessment of snowpack stability based on field observations and measurements remains a significant challenge that many researchers have tackled over the decades, yet a method that is both accurate and precise has not been achieved. The intuition of a highly experienced skier is insufficient, as evidenced by numerous accidents involving mountain professionals. Hardness tests of surface layers using a ski pole can refine initial impressions but are inadequate for comprehensive evaluation, and complete snowpack probing associated with a stratigraphic profile has demonstrated its limitations after more than fifty years of practice. The development of stability tests has provided notable progress, particularly by capturing the dynamic nature of slab release.

In our efforts to contribute to avalanche safety decisions concerning numerous road sectors in France (over 400), we have employed all the aforementioned approaches before focusing specifically on the primary stability tests commonly used:

- **CT - Compression Test** [Jamieson, 1999].
- **ECT - Extended Column Test** [Simenhois and Birkeland, 2006].
- **PST - Propagation Saw Test** [Gauthier and Jamieson, 2006, Sigrist and Schweizer, 2007].

After four seasons, it has become evident that each test type provides different information, with

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varying degrees of correlation to actual stability. Consequently, we developed a protocol [Pourraz et al., 2023b] systematically incorporating multiple tests at the same location (always two CTs, a priority PST, and an ECT under certain conditions). We have named this protocol **ROMANsns** (**R**éseau d'**O**bservations et de **M**esures **A**valanche et **N**eige en **s**ecteur **n**on **s**écurisé - Avalanche and Snow Observation and Measurement Network in Non-Secured Areas). This protocol is applied not on a fixed measurement site but throughout the mountainous terrain that we traverse from early winter until late spring.
With the ROMANsns protocol now supported by a mobile application for real-time data entry on smartphones and an online database since 2020, it is now feasible to propose a statistical analysis. The primary objective is to identify markers of confirmed instability. A sample of these tests was conducted on snowpacks "*presumed unstable*", defined based on proximity in space and time to observed avalanche events.
The implications of these tests for decision-making are discussed for institutional decision-makers, professionals operating in the field, and recreational practitioners.

## 2. MATERIALS & METHODS

A total of **736** ROMANsns tests, all conducted in accordance with the established protocol, were performed between December 11, 2020, and May 15, 2024. All tests were recorded and are available online at www.data-avalanche.org/romansns. The majority of these tests (551) were carried out by professional snow scientists from the ALEA consulting firm:

- Primarily as part of continuous winter monitoring for road protection in the Savoie, Isère, and Hautes-Alpes regions, commissioned by the respective Departmental Councils.
- A few were conducted within the scope of judicial investigations of avalanche accidents.

The remaining tests were performed by experienced and trained mountaineers.

### 2.1 Location of ROMANsns Tests

We conduct snow stability tests in areas where the snowpack appears most likely to be unstable, while avoiding hazardous locations by utilizing the terrain's features [Pourraz et al., 2023b]. This approach aligns with our professional objective: identifying the most dangerous slopes that require caution. Even when the situation seems uniformly stable, we still perform verification tests. The preliminary stability assessment is based on conventional field observations: variations in snowpack layer hardness, recent snowfall, warming, surrounding avalanche activity, etc. [Pourraz et al., 2023a]. The snowpack is classified as "*relatively stable*" when no recent avalanche activity is observed (except for glide avalanches), there is no recent snowfall or ongoing melting, etc. The snowpack is deemed "*relatively unstable*" when there are no clear signs of stability. The snowpack is considered "*presumed unstable*" when an avalanche has recently occurred nearby on a slope with similar characteristics (see Figure 1).

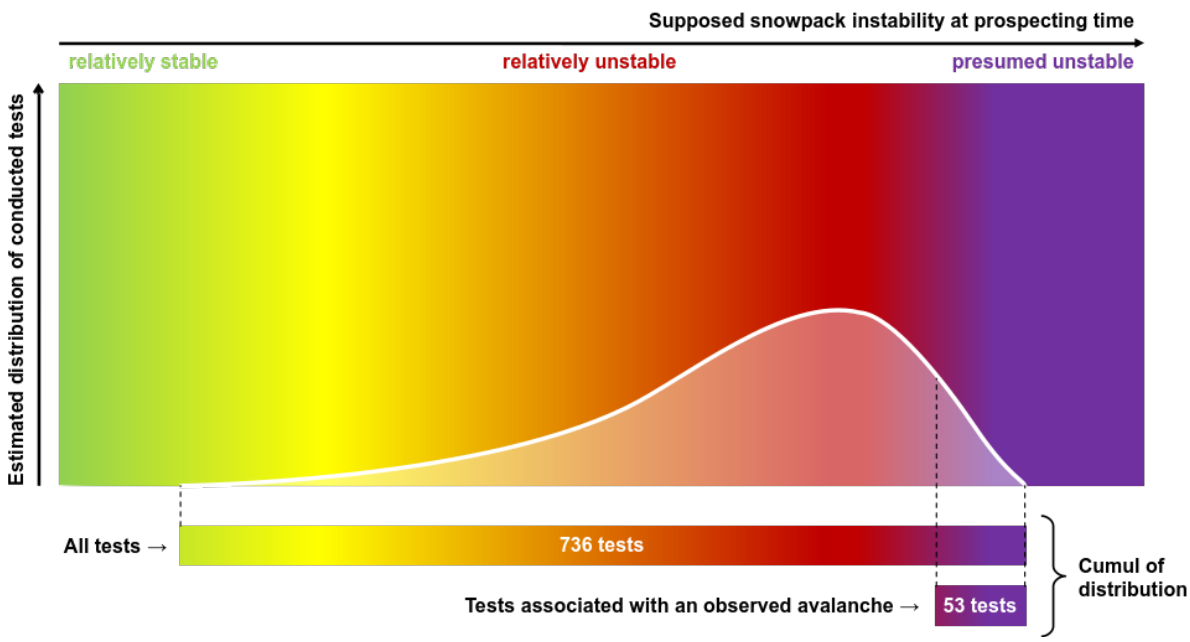


Figure 1: Symbolic distribution of ROMANsns tests

To describe a "*presumed unstable*" snowpack, we almost always manage to implement the ROMANsns protocol at the crown fracture of the avalanche. Since the slab has already released, the tests cannot be conducted exactly at the original slab location. However, examining at least one point at the crown fracture provides the most valuable information and ensures consistency in our approach. On the other hand, if snowpack stability tests are conducted "*near the avalanche*", the snowpack may differ from the one that triggered the slide due to factors such as wind, slope angle, exposure, etc.
Out of the 736 ROMANsns tests, 53 are directly associated with an observed avalanche that was subsequently recorded, geolocated, dated, and described as accurately as possible (circumstances, photos, etc.) on www.data-avalanche.org, an online associative database now containing 5,162 cases. Of these, 29 tests were conducted exactly at the crown fracture by at least one professional snow scientist from the ALEA team.
In the subsequent analysis, this classification of the snowpack should be considered when interpreting our statistical results: the total population of our tests does not represent the overall snowpack conditions in the mountains, but rather the situations we prioritized for study ("*presumed unstable*" or "*relatively unstable*").

### 2.2 ROMANsns test protocol

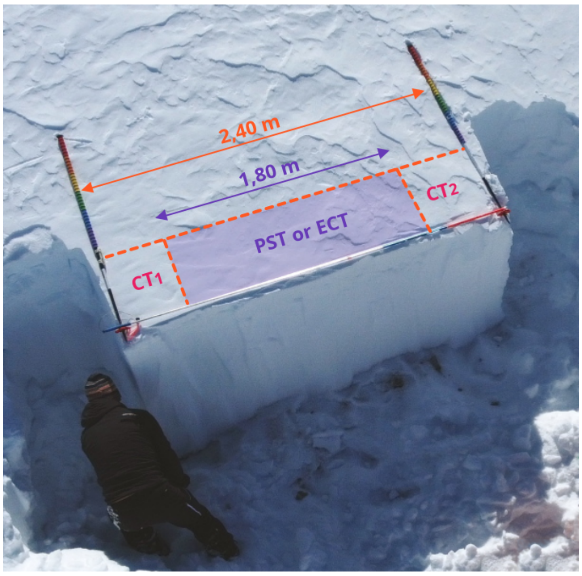


Figure 2: ROMANsns Protocol trench template and tests combination

Until the spring of 2023, the two CTs were used to determine which type of test would be performed next to evaluate the potential for crack propagation within the weak layer. A PST was chosen if the most critical weak layer was identified during the CTs or in the presence of a surface layer of loose snow; otherwise, ECT was selected [Pourraz et al., 2023b] (see Figure 2).
Now, even after conducting an ECT, a complementary PST is systematically performed on the weak layer identified as the most critical following the ECT. We have come to particularly value the PST for the following reasons:

- **Greater Observer Independence**:
  The PST is less dependent on the observer's technique (anyone can saw in a relatively consistent manner, whereas the force applied during a tap in an ECT can vary significantly).
- **Potentially Continuous Measurement**:
  The PST allows for a more precise measurement of the crack initiation length if necessary.
- **Independence from Surface Snow Quality**:
  The PST's results are not directly influenced by the surface snow's hardness or looseness, unlike the ECT, where outcomes can vary based on the surface conditions.
- **Lack of Disturbance from the "*Slab*" Effect**:
  The PST is not affected by the insulating properties of the slab during the test, a factor that can lead to false negatives in an ECT due to the thickness and quality of the snow above the weak layer.

This systematic application of the PST enhances the comparability of all tests within our database. An ECT is still performed if the PST yields a negative result, particularly if the weak layer appears easily triggerable during the CTs, especially in cases of wet snow, as discussed in Section 4.
All tests are systematically recorded on video and archived. Videos that we consider valuable for educational purposes are available online at www.youtube.com/channel/UCFB_Z_LSIXwfoyGnZDAV4RQ.

### 2.3 Test classification

The CT and PST tests are classified according to the criteria we proposed based on the 543 ROMANsns tests conducted between autumn 2020 and spring 2023 [Pourraz et al., 2023b]. The ECT tests, being less frequently conducted, were not included in this classification.
Our approach, informed by current understanding of slab avalanche triggering mechanisms, focuses on evaluating crack propagation within the buried weak layer. The key criteria are the ease of collapse within the weak layer during a CT (measured by the number of taps - see Table 1) and the ease of crack propagation within the weak layer during a PST (measured by the length of the pre-cut and the arrest condition for whether the propagation is complete or not - see Table 2).

| | Failure initiation |
|---|---|
| **Strong(CT)** | Spontaneous upon block isolation **or** 1 to 3 taps |
| **Moderate(CT)** | 4 to 6 taps |
| **Slight(CT)** | 7 to 9 taps |
| **Negative(CT)** | 10 or more taps **or** no crack |

Table 1: CT local crack classification

We found that using the "*number of taps*" as a criterion for evaluating a CT result was sufficient, as the main objective is to locate the weak layer where crack propagation will be tested. The variability in CT results observed even with tests conducted just 1.80 meters apart (on either side of the trench) reinforced this decision. Therefore, we did not adopt the usual CT classification (10 taps from wrist, elbow, shoulder) but focused solely on the number of elbow taps (see Table 1).

### *2.4 Data processing for tests associated with avalanches (presumed unstable snowpacks)*

All statistical analyses were performed automatically, particularly using the dates, times, and geolocations of the events. The classification of tests was also automated:

- **Classification based on distance from avalanche crown to test location**:
  To automatically calculate the distance between the test site and the location of an avalanche, we assumed the avalanche occurred at the same location as the test when the test was conducted precisely at the crown fracture.
- **Classification based on time interval between avalanche occurrence and test execution**:
  For this classification, we automatically calculated the time difference between the dates and times of the tests and those of the avalanches. We arbitrarily chose to distinguish between the following intervals:
  - ✓ **Less than 4 hours**.
  - ✓ **less than 36 hours (at the latest, the day after the avalanche)**.
  - ✓ **36 hours or more**.

  Since the exact timing of avalanche occurrences is often unknown, some approximations were necessary. However, these approximations have minimal impact on the results: if tests were conducted within 4 hours of the avalanche, the time of the avalanche is known with precision; if tests were conducted 36 hours or more after the avalanche, the exact time of the avalanche becomes irrelevant.

## 3. RESULTS

Only the results obtained from the PST and CT tests are presented here. For the CT tests, only the most reactive of both (the stronger CT) is considered.

### *3.1 Is the subset of tests associated with a recent avalanche different from the entire set of tests?*

The discriminating nature of the PST is evident, as more than ¾ of the tests (**79%**) were positive (considering **Strong(PST)** and **Moderate(PST)**) when associated with an avalanche, compared

| | Critical cut length | | Arrest condition |
|---|---|---|---|
| **Strong(PST)** | Spontaneous upon block isolation **or** Epsilon **or** 1/4 | **and** | None (complete propagation) |
| **Moderate(PST)** | Spontaneous upon block isolation **or** Epsilon **or** 1/4 | **and** | Takeover |
| **Moderate(PST)** | 1/3 **or** 1/2 | **and** | None (complete propagation) |
| **Slight(PST)** | Spontaneous upon block isolation **or** Epsilon **or** 1/4 | **and** | Incomplete |
| **Slight(PST)** | 1/3 **or** 1/2 | **and** | Takeover |
| **Slight(PST)** | 2/3 | **and** | None (complete propagation) |
| **Negative(PST)** | 1/3 **or** 1/2 | **and** | Incomplete |
| **Negative(PST)** | 2/3 | **and** | Takeover **or** Incomplete |
| **Negative(PST)** | Full | **and** | / |

Table 2: PST crack propagation classification

to **63%** when they were not associated with an avalanche (see Figure 3).

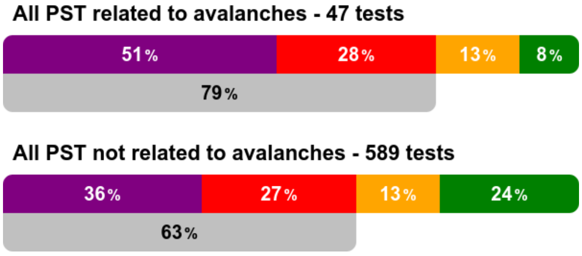


Figure 3: PST crack propagation statistics

The discriminating nature of the CT could also be considered when looking solely at those tests associated with an avalanche, as **96%** of the tests were positive (considering **Strong**$_{(CT)}$ and **Moderate**$_{(CT)}$) when associated with an avalanche. However, it's important to note that **91%** of the tests were also positive even when not associated with an avalanche (see Figure 4). The difference is less significant for CTs than what is observed for PSTs.

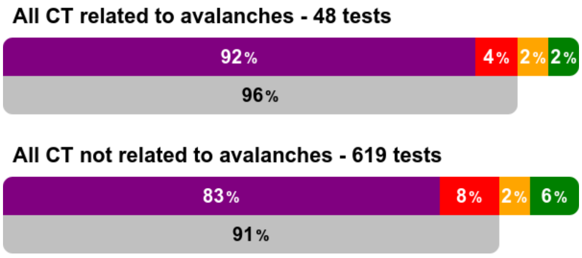


Figure 4: CT local crack statistics

These results indicate significant but not very pronounced differences. We sought to delve deeper by closely examining the series of tests associated with avalanches, considering the time interval and distance between the moment and location of the tests and the crown fracture of the associated avalanche.

### 3.2 *What do tests conducted near a recent avalanche reveal?*

For this part of the study, we included only the tests conducted by at least one professional snow scientist from the ALEA team. We differentiated between tests performed exactly at the crown fracture (where the distance is considered 0) and those conducted slightly further away (ranging from 15 m to 571 m in our dataset).
The CTs are almost always positive at the crown fracture, with **96%** classified as **Strong**$_{(CT)}$ and **100%** when considering both **Strong**$_{(CT)}$ and **Moderate**$_{(CT)}$ results. However, as the distance from the crown increases, the positivity rate decreases slightly, with **82%** classified as **Strong**$_{(CT)}$ and **88%** when considering both **Strong**$_{(CT)}$ and **Moderate**$_{(CT)}$ results (see Figure 5).

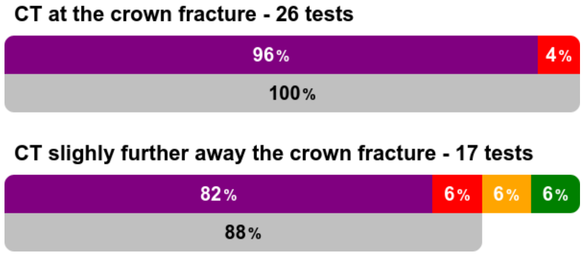


Figure 5: Avalanche-related CT local crack statistics

The PSTs are mostly positive when conducted at the crown fracture location, with **63%** classified as **Strong**$_{(PST)}$ and **88%** when considering both **Strong**$_{(PST)}$ and **Moderate**$_{(PST)}$ results (see Figure 6). However, these tests show a significantly lower positive rate compared to the CTs.
When tests are conducted further away from the crown fracture, the results are much more varied, with only **37%** classified as **Strong**$_{(PST)}$ and **56%** when considering both **Strong**$_{(PST)}$ and **Moderate**$_{(PST)}$ results.

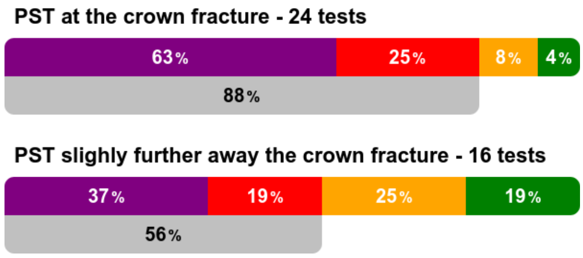


Figure 6: Avalanche-related PST crack propagation statistics

### 3.3 *Impact of time interval between avalanche occurrence and testing*

Using the same sample of tests as previously, we distinguished *a priori* between tests conducted immediately after the avalanche (within < 4 hours, 9 cases), those conducted shortly after the avalanche, often the next day (within < 36 hours, 35 cases), and those conducted later (often 2 days, occasionally 7 to 10 days, 11 cases).

The CTs are always positive when conducted at the crown fracture within 36 hours of the avalanche (**100% Strong**$_{(CT)}$) and are only slightly less positive when conducted further away, both in space and time (**84%** to **80% Strong**$_{(CT)}$) (see Figure 7).

The PSTs are always positive when conducted at the crown fracture within 4 hours of the avalanche (**100% Strong**$_{(PST)}$). However, their positivity decreases significantly as the distance from the fracture and the time since the avalanche increase (**67%** to **20% Strong**$_{(PST)}$) (see Figure 8).

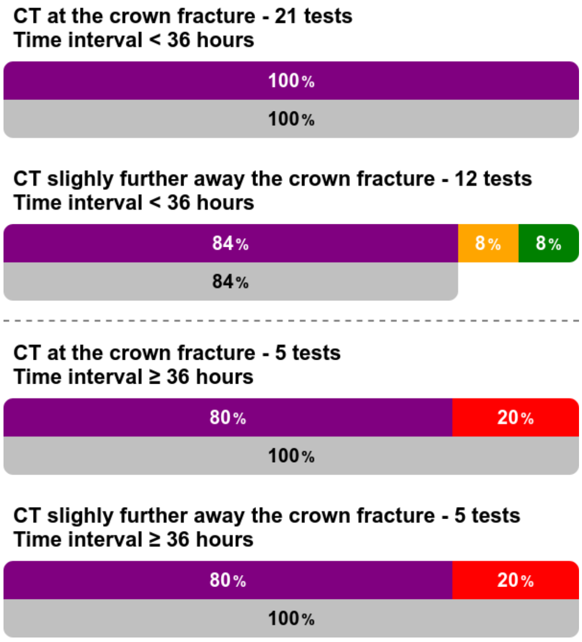


Figure 7: Avalanche-related CT local crack statistics depending on time intervals

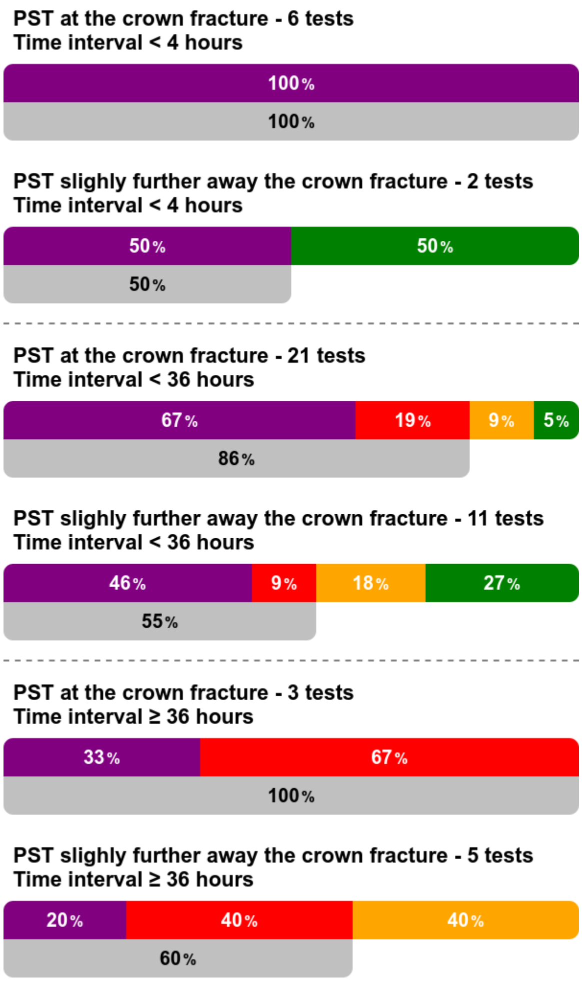


Figure 8: Avalanche-related PST crack propagation statistics depending on time intervals

## 4. DISCUSSION

This study is unique because numerous field measurements were conducted according to a robust protocol in unsecured areas, including at the sites of recent avalanche fractures. However, it suffers from a sample size of avalanche-associated cases that is still too small for significant statistical analysis, so only trends are proposed. Discrepancies are also discussed.

An initial analysis (see Section 3.1) showed relatively few differences between the population of tests conducted at avalanche fracture sites and those conducted elsewhere. Indeed, we often found weak layers that reacted positively to CTs, but this is at least partly due to our strategy of selecting test sites: we seek out the most unstable snowpacks in the explored area. Positive PST responses are less common. This observation challenges potential decisions based solely on stratigraphic analysis. Based on the CTs, a situation would often be considered dangerous when it is not, while the PST results would lead to fewer such errors.

However, snowpack tests conducted at avalanche fracture sites shortly after they occurred are noteworthy. Firstly, we observed that PSTs conducted at the crown fracture within 4 hours of the avalanche are consistently positive (**100% Strong$_{(PST)}$**, 6 cases). We assume that the number of documented cases is small, which is understandable given the challenging nature of implementing a relatively complex measurement protocol: triggering a slab avalanche, then instead of fleeing, we approach the fracture, deploy the instruments, take videos, etc. This was, however, our priority objective during the last winter of 2023-2024.

When moving away from the fracture, the results of the CTs are less consistently positive but remain predominantly so. The same applies when measurements are taken later. We interpret this result as an illustration of the limited significance of CTs for stability assessment. PSTs, on the other hand, quickly become less frequently positive as the distance from the fracture increases or when they are not conducted immediately after the avalanche.

Beyond these trends, a few specific cases caught our attention by not conforming to them at all:

- The most curious instance involved a dramatic avalanche, where numerous tests conducted less than 24 hours later at various points along the crown fracture showed no propagation in the weak layer, whether through PST or ECT. The implicated weak layer was clearly temporary (not detectable during typical skiing practices), the slope angle was steep (close to 40°), and the stress was significant (many skiers on the slope simultaneously).

- In another case, the PST was negative while both CTs were positive in a weak layer of wet snow. An ECT was then conducted, which turned out positive under low stress. The avalanche that occurred a few days later exactly at that spot (preventive triggering we had recommended) now leads us to conduct ECTs more systematically after a negative PST in a weak layer that is easily triggered during CTs, particularly in wet snow conditions.
- We also triggered several wet snow avalanches near a slope where we had conducted negative PSTs but positive CTs (**Strong$_{(CT)}$**). These were loose avalanches, consistent with our test results (existing weak layer but no propagation).
- Lastly, interesting specific situations have also been formally described. For example, even though it is often mentioned that "*a dry-snow slab avalanche release is the result of failure initiation in a weak snowpack layer buried below a cohesive snow slab*" [Benedetti et al., 2019, Bobillier et al., 2024], we could document a situation involving very low cohesion powder snow slab (20 cm at 60 kg/m³ above 15 cm at 120 kg/m³ – $T_{air}$ = -7.3℃) associated with high avalanche activity: www.data-avalanche.org/avalanche/1609788222903.

From an operational standpoint, the ROMANsns protocol has already been very useful for road protection in 3 French Departments. Globally positive results without any avalanche occurrence inform us of a high probability of avalanches if the situation worsens due to factors such as melting or, more importantly, new loads. Our videos of positive tests then serve as effective arguments for discussing the implementation of binding avalanche control (e.g., helicopter-triggered avalanche control). The opposite is also true. Globally negative results have sometimes served as arguments to keep a road open or to delay an avalanche control.
Regarding mountain professionals in the field, the benefit of the ROMANsns protocol is more mixed: its complete implementation is relatively complex, but simplified versions can be used to good effect. In general, understanding the protocol is fruitful, and the demonstration of the slab release mechanism is convincing. Here too, sharing online videos is a potentially effective prevention tool.
For all users (professionals and recreationists alike), the results of each test are disseminated via the SYNTHESIS tool (www.data-avalanche.org/synthesis/ - [Pourraz et al., 2023c]), representing valuable information in the decision-making process [Pourraz et al., 2023a].

## 5. CONCLUSION & PERSPECTIVES

Operational management of avalanche risk always raises very concrete questions that remain difficult to answer accurately and with solid justification, despite the often significant stakes involved. This could concern recreational activities in the mountains, where the danger can often be avoided if there is any doubt. However, when it comes to closing a road for an indefinite period or carrying out a demanding preventive triggering operation, a clear and well-supported opinion is always expected by institutional decision-makers. With this in mind, an investigation protocol for the snowpack was developed, based on classical methods (e.g., stratigraphic profiles) supplemented by a combination of standard snowpack tests (CT, ECT, PST), with specific conditions and objectives defined for their application (ROMANsns process: Avalanche and Snow Observation and Measurement Network in Non-Secured Areas).

To understand the significance of our results, we compared all tests conducted as part of "*permanent snowpack monitoring*" with those obtained specifically near and/or shortly after the summit crown fracture of a slab avalanche (**53** tests associated with an avalanche, out of a total of **736** tests conducted over the last four winter seasons). The snowpacks in the latter category were classified as "*presumed unstable*", distinct from those classified, based on field estimates, as "*relatively stable*" and "*relatively unstable*".
The results are notable in that they do not show any striking singularity of the presumed unstable tests compared to all tests, which is not good news (it would be unrealistic, at present, to estimate that an avalanche will occur solely based on a stratigraphic analysis). Only the PSTs conducted at the avalanche fracture site less than 4 hours after its occurrence stand out with a systematic maximum sensitivity to the crack initiation and propagation in the identified weak layer (6 tests). Such sensitivity becomes less frequent as one moves away from the fracture site or as the time gap between the avalanche and the tests increases.
To obtain this result, we specifically studied all tests associated with an avalanche and conducted by the professional snow scientists at ALEA (**43** tests). CTs do not have this discriminating characteristic: they also show maximum sensitivity at the avalanche fracture site less than 4 hours after its occurrence, but produce similar results with significant frequency in many other situations. We did not subject the ECT to such analysis due to an insufficient number of tests.

However, the ROMANsns protocol has allowed us to better understand and make better use of the respective contributions of CTs (quick identification of weak layers and assessment of snowpack continuity), ECTs (identification of the most sensitive weak layer for crack propagation in complex snowpacks), and PSTs (measurement of the ease of crack initiation and propagation in the weak layer, which we consider the most precise). It has also led us to question test results based on the characteristics of the weak layer (e.g., are ECTs more significant than PSTs in the case of a wet weak layer?). The relevance of the thresholds we had previously established to identify markers of instability has been confirmed. Instability can thus be anticipated and subsequently verified, as well as the return to stability.

From an operational standpoint for helping to manage avalanche risk on the roads of three French departments, the ROMANsns process now provides an additional set of field data that has proven very useful, both for decision-making itself and for the preceding information-sharing process. It has become significantly easier to estimate what will happen on a slope we recently tested or to extrapolate observations made at a specific location (where else might an avalanche similar to the one just reported occur?). It is also a particularly effective educational tool for training mountain professionals.

Finally, highlighting differences in test results based on test conditions should lead to more systematically specifying these conditions when a test is intended to describe or explain an avalanche, particularly:

- What is the distance between the test site and the avalanche's summit fracture site?
- What is the time interval between the test and the avalanche?

Increased efficiency could thus be achieved in research work as well as in judicial expertise.
These studies are still exploratory and, of course, suffer from an insufficient amount of data. We hope for an extension of the implementation of the ROMANsns process and the tools developed for this purpose, as their daily application often leads us to reevaluate our field estimates and allows us to learn a little more each day.

## ACKNOWLEDGEMENT

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