A Portable, Variable-Speed, Penetrometer for Snow Pit Evaluation

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Abstract

A new, portable, variable-speed, penetronmeter for snow-pit stability evaluation has been developed (named "SABRE").

Despite the heavy reliance on snow-pit information in the avalanche forecasters' arsenal of tools, it has been demonstrated that snow-pits on a single slope have highly variable characteristics. The thirty-five to forty minutes required for digging a snow-pit limits the number of snow-pit tests that can be performed. The portable snow-probe is designed to obtain information on the stiffness, hardness, stability and temperature gradient of the snow pack as quickly as possible. The hand-held probe consists of a high-sensitivity force sensor, an accelerometer, an embedded processor (computer) with a program to correlate the acceleration changes with the force and positional information.

SABRE enables the test to be performed in roughly 16 seconds and the calculation of the snow pit profiles takes approximately 2 minutes. Therefore, multiple tests can be performed on any given slope with minimal hassle. Multiple tests mean a greater sample size with a concurrent increase in the validity of the test. Snow pit profiles can be displayed in both graphic and text-based formats on the specially built hand-held computer. Data from up to 80 pushes can be stored on the unit itself and can later be downloaded to a PC for storage and subsequent analyses. During the course of our research, 3-Dimensional contour plots derived from full across-slope profiling have shown zones of instabilities (subsequently confirmed by an artificially released avalanche)

Keywords

Avalanches, avalanche forecasting, avalanche protection

1. Introduction

The detection and classification of snow layers are extremely important when determining the stability of the snow pack in relation to avalanche potential. US Cold Regions Research Laboratories' research showed that aside from avalanche studies (i.e. release mechanisms, particle movement and impact effects, and effects on avalanche defenses), relatively infrequent use is made of snow mechanics. Perhaps the most important reason why this is so is that there are few commercial or governmental activities that absolutely require knowledge of snow properties and processes.

It is apparent that the current systems of avalanche control data collection could be improved. New devices to speed data collection and achieve more accurate results of snowpack properties would be beneficial.

The snow stability assessment system- *SABRE*- was developed for Himachal Helicopter Skiing (HHS) to establish a faster and more accurate data collection for the ski runs used by the operation. SABRE is a hardware-software embedded computer system designed to determine the snow slope stability (figure 1). The portable snow probe is designed to obtain information on the stiffness, hardness, stability and temperature gradient of the snow pack as quickly as possible. SABRE complements the "snow-pit test" and other tests currently undertaken by HHS.

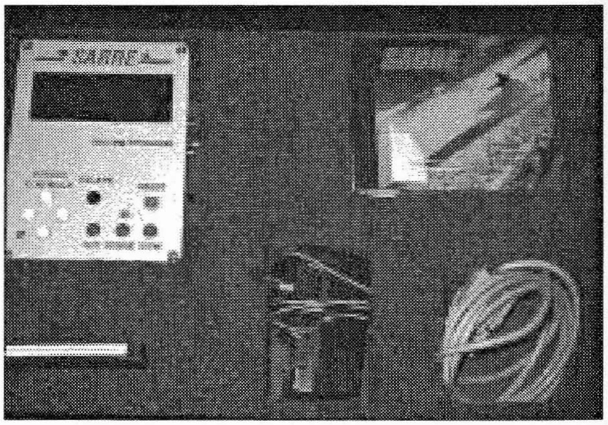

Figure 1 Early version of the SABRE Probe in its case with cables and software

The standard snow-pit test assigns primary importance to the hand-test of the snow-pack. This leads to the "standard pit hardness profile". The hardness measurement is given a nominative scale of; "fist", "four fingers", "single finger", "pencil" and "knife". The subjective nature of this test is evident by the very definitions used for these terms. For example, "fist" hardness is defined as hardness of a snow-pack such that an operator can push into the snow with "*moderate ease*" using a gloved fist with a force of 10 to 15 Newtons. The ambiguity of the term "moderate ease" and the 50% margin of error allowed in the force required render this type of measurement subjective. Temperature profile is of secondary importance in the snow-pit test. The length of time taken for a full snow-pit test (approximately 35 minutes) restricts its use.

Despite the heavy reliance on snow-pit information in the avalanche forecasters' arsenal of tools, it can be demonstrated that snow-pits on a single slope are highly variable. Results from snow-pits dug only twenty metres apart can vary significantly.

In contrast, SABRE enables this test to be performed in less than two minutes (figure 2). Hence, it is practical to perform multiple tests on a slope. The increased sample size increases the statistical power and the validity of the test.

Data is displayed on the hand-held computer within 50 seconds of the push. The data can be downloaded to a PC for subsequent analyses. The system has been designed to be user-friendly, portable and to fit easily into a small backpack.

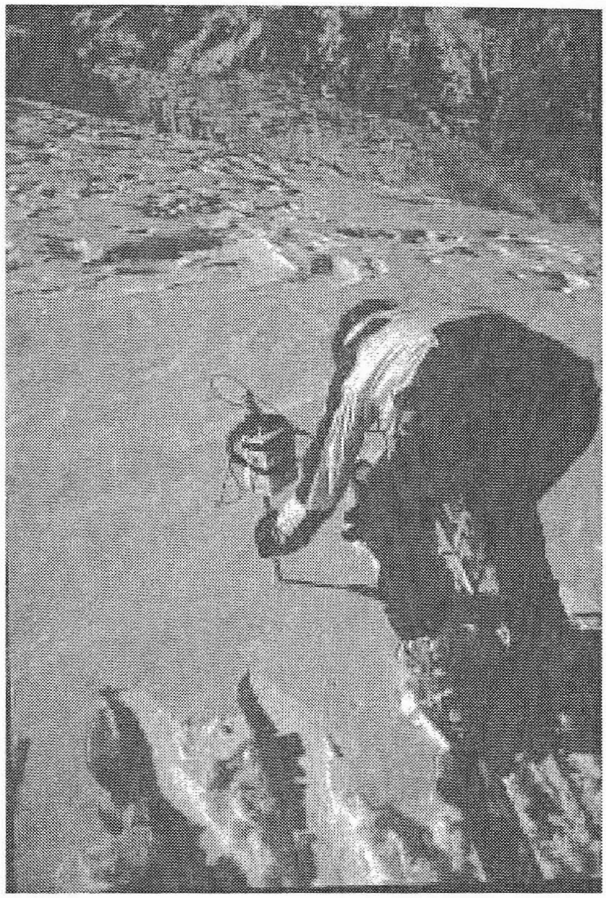

Figure 2 Using the SABRE Probe

2. Construction

The primary consideration during the design process was to obtain an apparatus that would be extremely portable and easy to use. The setup would also be quick and not require tripods or drive motors. Thus, an important feature of the design is that the probe could be manually inserted into the snow. A manual insertion leads to acceleration and velocity changes. As a consequence it was necessary to design a system that could (a) account for changes in the acceleration, (b) recovery of the distance into the snowpack and (c) correct for velocity and inertia changes. A number of successive designs and refinements of the system have occurred over the 1999, 2000 and 2001 winter seasons. The current design includes a purpose-built force-sensor, a micro electronically machined sensor (accelerometer), an embedded processor (computer), flash memory and graphics display. An embedded program has been written over the last 2 years for the processing of data collected from the sensors and subsequent display on the screen. The complete system is portable and weighs less than 2kg.

The force cell is a specially constructed to reduce the interference of external noise in the load cell signals. Three primary signals are taken during the push with a resolution of 500 readings per second. These are:

1. Acceleration
2. Force
3. Temperature

The process to obtain the final layer definition is as follows: The acceleration is integrated to velocity and a check is made based on the start and finish of the push to ensure that the velocity is zero at both ends of the push. Data slope adjustments are performed, which are used to modify the acceleration, which is then integrated again. Once the velocity is zeroed a final integration is performed to compute displacement. Over-sampling is used during the integration phase to ensure noise reduction of the signal. The displacement is then related to the force reading. The force reading is also over-sampled and averaged.

Once the velocity of the push is calculated a "look up" table can be used, based on the force and velocity to cancel out any inertial effects leading to incorrect force readings due to strain hardening of the snow pack.

The data for the push is then stored to the flash memory. To display on the graphics screen with a limited resolution and to perform pattern recognition of the layers, frequency decimation and smoothing of the data is performed. Frequency decimation is performed during the smoothing to ensure that all peaks and valleys are maintained. Approximately 8000 readings are decimated to around 120 (figure 3). This figure shows that the important information is maintained during the process.

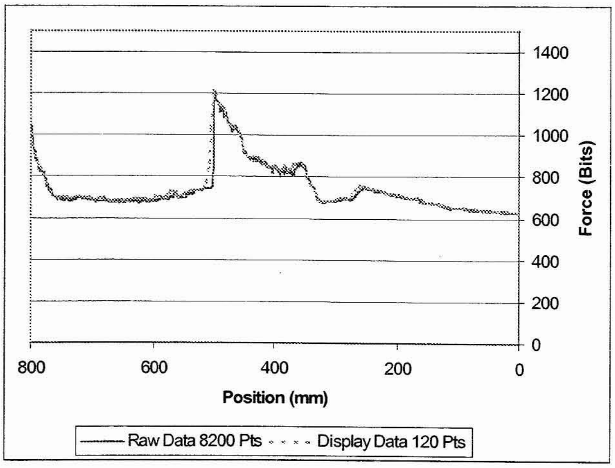

Figure 3 Frequency and smoothing decimation of the data

A pattern recognition program is used to break up the readings into layers more commonly used by the ski guides. Pattern recognition is performed using a two step iterative process.

The algorithm used is rule-based with a large number of logic statements to search the snow pack for layer breaks. The process is analogous to that used by the guide during the snow pit test. Each layer is stored with the depth and an additional algorithm is used to determine the appropriate force for that layer. Finally a "lookup" table is used that correlates the force reading (in Newtons) hand scale used by the guides. This "lookup" table has been the result of a large number of tests taken on a significant number of different snow packs and avalanche conditions.

3. Results

In this paper a description of the force data is discussed. Results are shown for test data taken during the 2001 ski season. The 2001 season in the Indian Himalayas was unusual, with significantly lower than expected snowfall. Early season falls were followed by a long time period (four weeks) where there was little to no snowfall and higher than expected temperatures. This led to both destructive metamorphism (TG) of the snow pack and formation of wind slab and wind crusts.

Development of depth hoar layers was also evident in the early snowfall followed by compaction of the more recent snowfalls. Standard snow pack testing which included snow-pit tests, Rutschblock tests, compression tests and shovel shear tests were performed. As expected, the tests revealed significant depth instabilities occurring on many slopes. Tests using the SABRE probe were performed in conjunction with snow-pit tests and the results correlated. A sample of the tests performed is discussed in the following sections.

The first test was conducted on 3 Feburary 2001 on a north-west facing slope at 4100 metres above sea level with an incline of 30°. A typical acceleration and velocity trace from this slope is shown in figure 4. The acceleration trace is the thicker line.

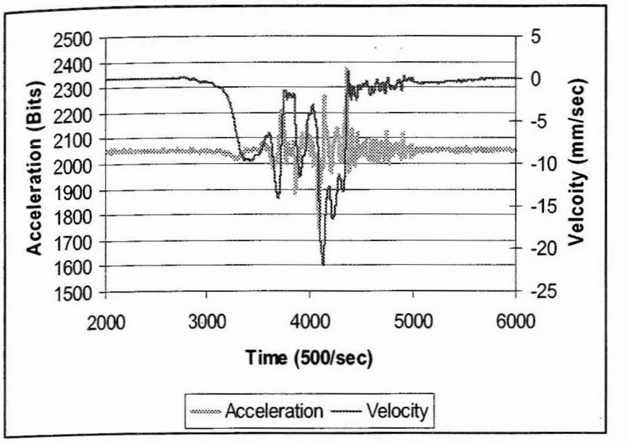

Figure 4 Acceleration Data Taken during Push

During the push, significant changes occurred in the acceleration. As expected, integration of the acceleration partially smoothed out the rapid change. The velocity changes displayed in figure 4 occurred as the operator moved his hands down the pole and also as he broke through harder layers into weaker layers.

The data was then integrated again to give displacement and correlated with the hand-pit test and probe force data. The completed analysis is shown in figure 5. The vertical scale shows both force in Newtons and a correlation to the standard snow-pit test scales. Snow pit tests were performed to confirm the probe data. The straight lines plotted in figure 5 display the hand snow-pit test data. The snow pit data showed the first two layers to be partially settled snow. Layer 3 was rounded grains with Layer 4 as facets. The hardest layer (Pen, Layer 5) was both facets and rounded grains falling to fist for the final layer (Number 6), which started as facets and ended in depth hoar at the ground.

The results showed that a significant correlation exists between the hand test and the probe data. A visual inspection of the probe data revealed the existence of approximately 6 layers. The probe data agreed well with the snowpit test results. The major difference was the fourth layer. The snowpit tests showed a reading of fist whereas the probe data gave a varying reading between hand and finger. The change between layers four and five was abrupt in the snowpit test whereas the probe found a gradually increasing hardness from finger into the pen layer. At the bottom of the pen layer at the interface between layer five and layer six, the snowpit test registered an abrupt change to fist. But the probe showed that the transition between these layers was not quite so sudden. The layer started at mid hand and gradually decreased to fist. This was confirmed in the snowpit test data as the sixth layer starting as facets before changing to depth hoar.

The shovel shear test and the Rutschblock test showed a failure occurring at the bottom of the fifth layer (Rutschblock score 4). A conservative interpretation would indicate that this slope at Rutschblock four was no longer ski-able.

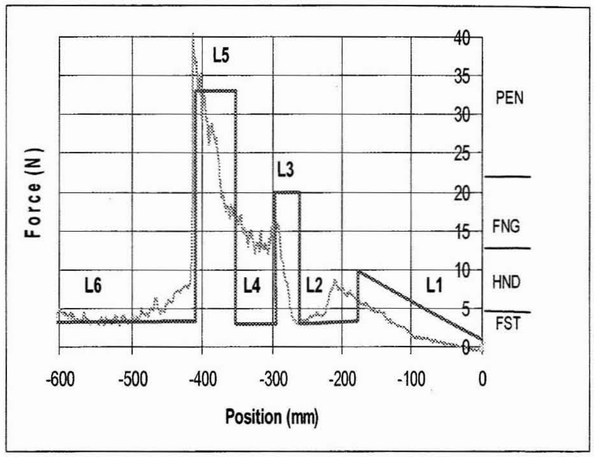

Figure 5 Comparison of hand pit test data with probe data

Pattern recognition software calculated a similar number of layers as found in the snowpit test (figure 6). The algorithms used show both the layer change and the slope change. Note that the first layer hardens from fist through to hand and is shown as a single layer as no abrupt change occurs.

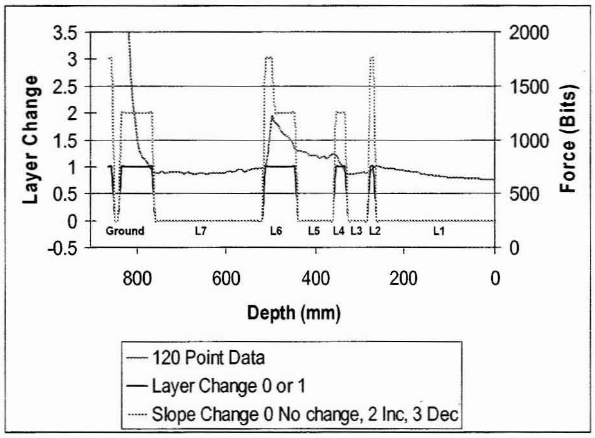

Figure 6 Pattern recognition of the layers

Statistical analysis was carried out on a large number of adjacent probe tests to ensure consistency of pushes. Examples of these tests were carried out on the 6th of February 2001 on a northwest-facing slope at 4285 m.a.s.l with a slope incline of 16°.

Acceleration and velocity time profiles for two traces (one thick line and one thin line) are shown in figures 7 and 8.

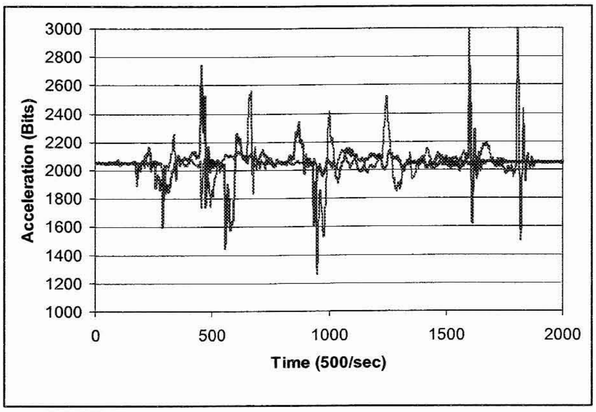

Figure 7 Acceleration time profiles for two pushes

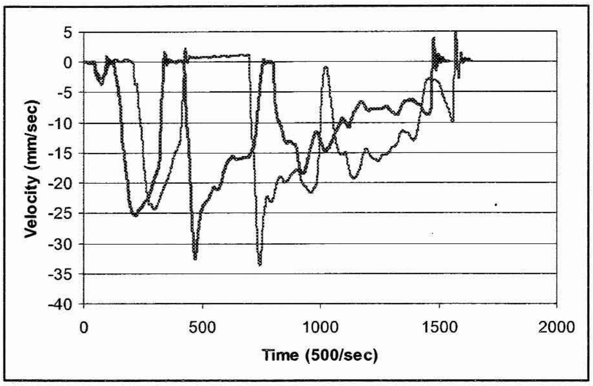

Figure 8 Velocity time profiles for two pushes

The acceleration data appears to show very little correlation between the two pushes. Both the number of peaks and the intensity of the peaks are different as well the overall time for the two pushes. Some similarities are noted. For example, a peak that occurs in one trace at just above the time reading of 500 is similar in form to the peak that occurs just below the time reading of 1000 for the other trace.

Figure 8 also indicates that, although the operator may believe that his push was steady, substantial velocity changes occur. A similar form is noted between the two velocity plots. Again the time for the plots is different. On at least two occasions during both pushes the velocity drops to almost zero. The first velocity drop appears to occur when the probe hits a pronounced hard layer in the snow pack.

The non-correlated and non-normalized force time data is shown in figure 9. The force data is shown in "bit" form, as it is stored. As the time base of the push is different, the plots appear to show very little peak to peak correlation. However, some similarities are apparent despite differences in heights and compression.

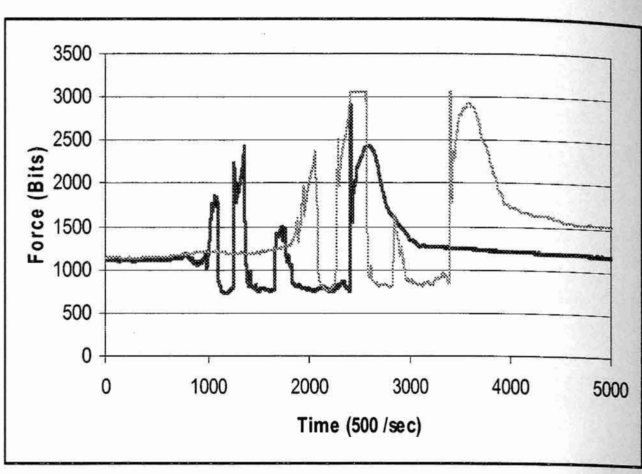

Figure 9 Non-correlated or normalised Force Time data for two pushes

Using the velocity time profile and integrating, this again produces a displacement time plot. Using the displacement plot, the velocity plot and the force plot, it is possible to de-convolute the data to give the final force displacement plot (figure 10). The force displacement plots in figure 10 show that tests are repeatable. Correlation between the tests exceeds 0.97 based on peak strength, number of peaks and depth of layer.

The force displacement plot shows excellent overlay, particularly in comparison to the time-based plot of force shown in figure 9. Note that the softer sections now appear stretched in comparison to figure 9 due to the faster velocity through the weaker zones. The data showed approximately 8 layers. Starting with a wind affected/compacted surface layer. A critical layer occurs at approximately 300 mm with a high degree of hardness and weak layers occurring both above and below this layer. Both plots show reasonable depth correlation as well.

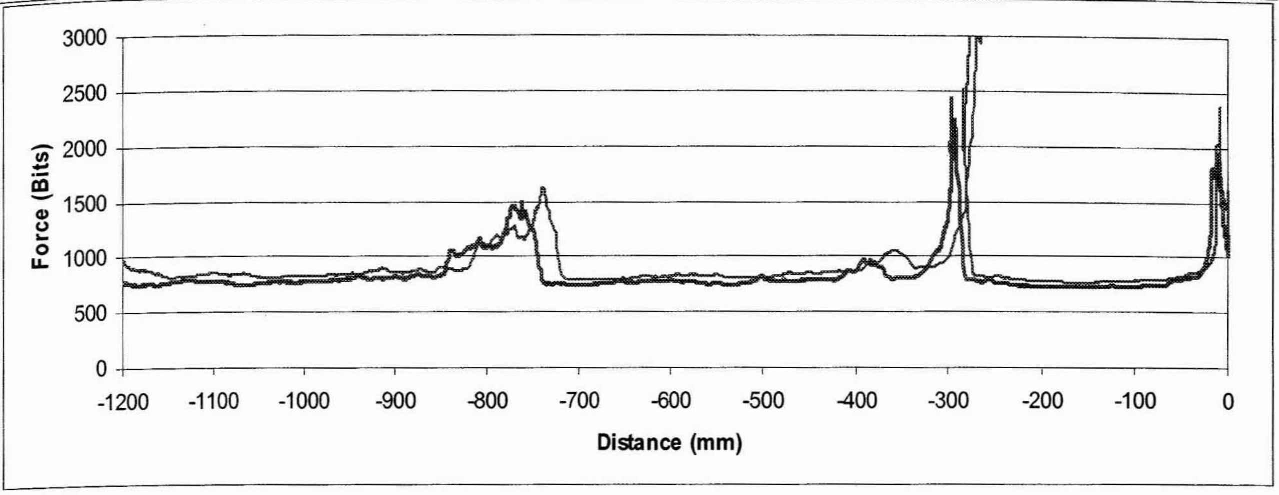

Figure 10 Correlated Force Distance profiles for two pushes

Snowpit tests were dug to confirm the data shown in figure 10. Figure 11 illustrates the snowpit test in comparison with the probe data. The probe data has been adjusted to Newtons and calibrated with the snow-snowpit test scale.

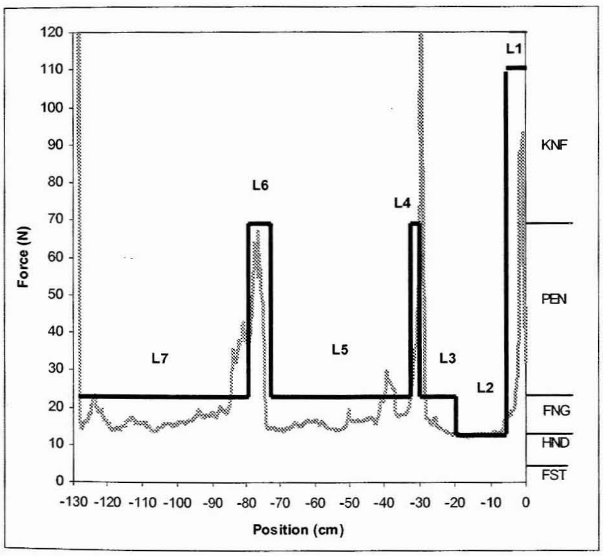

Figure 11 Snowpit test confirmed the ability of the probe to detect thin hard layers

Standard tests on this slope showed again pronounced instabilities occurring at approximately 30 cm and 80 cm depths. The probe data agreed well with the snow-pit data. Snowpit measurements showed a total of 7 layers with the probe giving 9 layers. Significantly, the two major layers at 30 cm and 80 cm are confirmed in both tests. The snowpit data showed all layers to be faceted crystals with the exception of the 7th (final layer). This layer showed a mixture of facets and depth hoar. Grain size for the top layers was approximately 0.5mm and up to 2 mm for layers 6 and 7.

The two harder layers showed substantial instabilities during shovel shear and shovel compression tests. The probe data showed these two layers to be harder than those indicated by the snowpit test.

4. Cross Slope Profiles

An important feature of the probe is the ability to take multiple readings across the slope quickly due in part to not having to take off one's skis and thus be able to ski from position to position. Numerous snow profiles were obtained during the 2001 season. A profile taken on the same slope as figure 10 will be illustrated. This test continued from the slope towards the ridgeline and extended for a distance of 60 metres. A number of the two dimensional profiles are shown in figure 12. The changing nature of the slope is demonstrated by the thicker plotted line that indicates the hard layer occurring at 30 cm has disappeared.

A more useful plot is to take the two-dimensional profiles (figure 12) and generate a three dimensional cross slope contour plot, (figure 13). The horizontal axis is the distance across the slope; the vertical axis is depth into the snow pack. To visualize this image, imagine a vertical cut into the snow pack across the entire slope. It is a contour map derived from multiple snow pits. Interpolation has been used between each successive probe.

The light grey to white shades indicate softer snow pack in the range fist to hand with the dark grey to black indicating pen to knife. The ridge as expected was found to be more stable than the slope. The slope showed: a wind affected slab with surface wind crust, a hard thin knife layer and a thicker hard pen layer. Moving towards the ridge (the left of the chart, 0 metres) the wind-crust lessened, as did the knife and pen layers. The ridge showed little wind compaction or substantial layer changes. Some minor changes were evident at 600 mm but were not significant. It was estimated that the ridge was ski-able but the slope was extremely unstable. This was proved subsequently with an artificial release by bombing the slope with a big lump of ice.

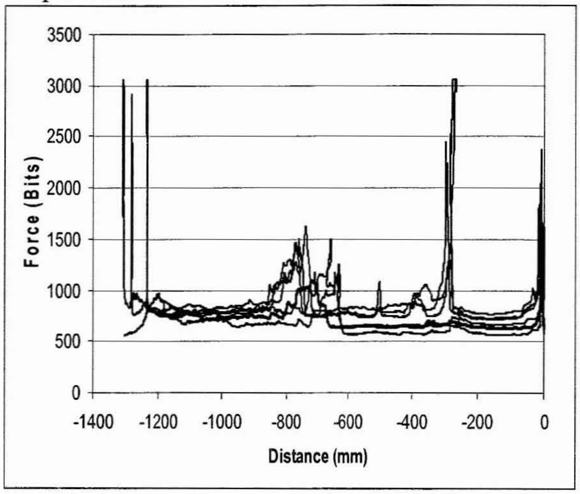

Figure 12 Multiple two dimensional probes taken at equal distances across the slope

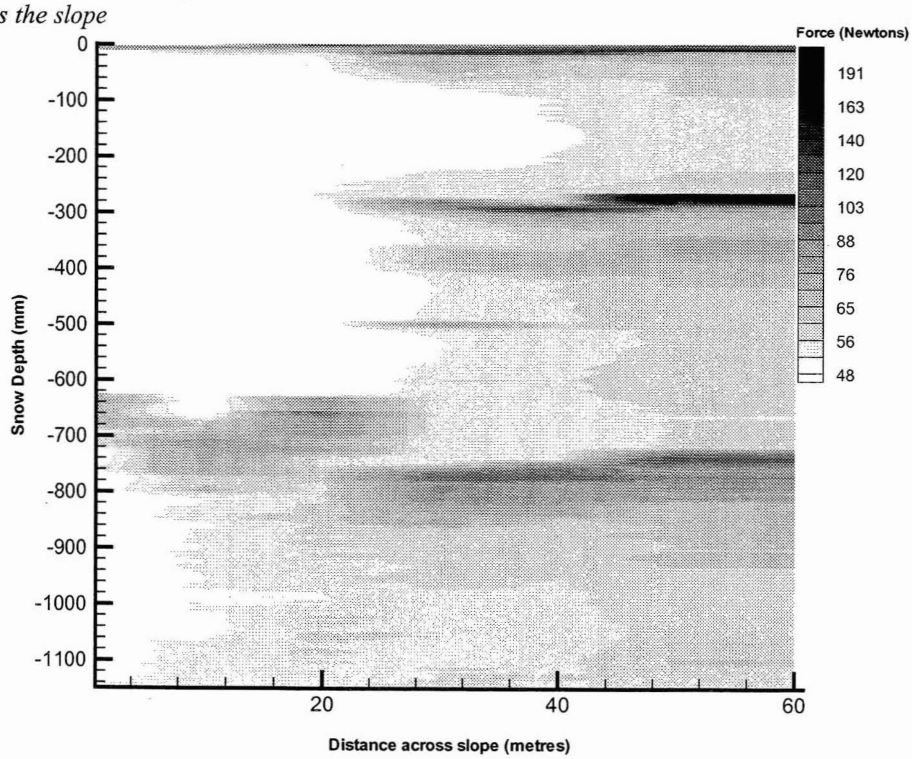

Figure 13. Contour plot of data from figure 12

5. Conclusion

The SABRE probe allows snow profiles to be taken quickly. The absence of subjective interpretation when operating the probe enables the collection of objective, quantitative measurements of snow pack strength and subsequent assessment of stability. Data taken by the probe correlated well with snow-pit data and any discrepancies shown was due to the subjective nature of the snowpit tests. Cross slope profiles can be developed and give a powerful added insight into slope conditions. Current development aims to improve distance measurement and reduce both the size and weight of the device.