Meteorological Factors Associated with Avalanches
in the Lake Shikotsu Area
and Their Application to Road Management

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1. Introduction

Countermeasures against avalanches have been improved and effectively implemented on roads in cold, snowy regions.   However, when avalanches are greater in scale than the design capacity of the countermeasures, they sometimes cause road closure.   As road administrators are required to make quick, proper decisions regarding such events, their accurate understanding of avalanche likelihood is crucial.

This study aims to assist road management by clarifying localized formation mechanisms of avalanches in Hokkaido and establishing a simplified method of determining the avalanche likelihood.   This paper investigates the relationship between avalanche formation and meteorological conditions on National Highway 453 in the Lake Shikotsu area, toward establishing a method of determining the avalanche likelihood in a specific area.   We report the results of an experiment using the method in road management.

2. Outline of the investigated section

The section investigated in this study measures the nearly 5 km between Kilometer Post (KP)42 and KP47 on National Highway 453 along Lake Shikotsu in Chitose, Hokkaido (Figure 1).   This section was hit by avalanches almost simultaneously at 16 locations on February 1, 2001, holding up buses and cars. As a consequence of this disaster, a study on avalanches in this area was launched.   The road section runs along Lake Shikotsu at the foot of Mt. Mombetsu.   The slopes adjoining the section have a gradient of 35˚ and face southwest.   The vegetation is rather sparse: The uppermost part of the slope is bare ground and shrubs; halfway down is mostly broadleaf tree; and the slope immediately above the road is grassy.
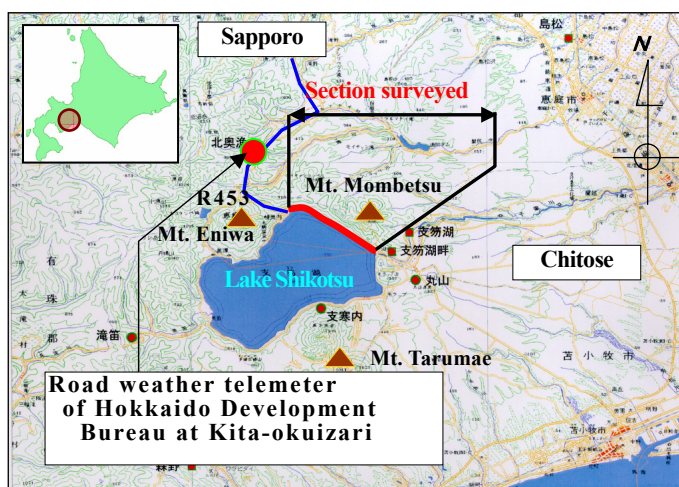

Figure 1 Section surveyed

3. Hypothesized avalanche formation process

Figure 2 shows changes in temperature and snow depth before and after the avalanche on February 1, 2001. Previous examinations on meteorological conditions at the time of avalanches on roads near Lake Shikotsu[1] identified a relationship between avalanche and a weather pattern in which a low-pressure system approaching from the southwest brings a rise in temperature accompanied by heavy snowfall. Such snowfall is assumed to abruptly increase the snow depth, thereby increasing the load that new snow exerts on previously fallen snow and causing the driving force to exceed the resistance force. This eventually results in a surface avalanche.
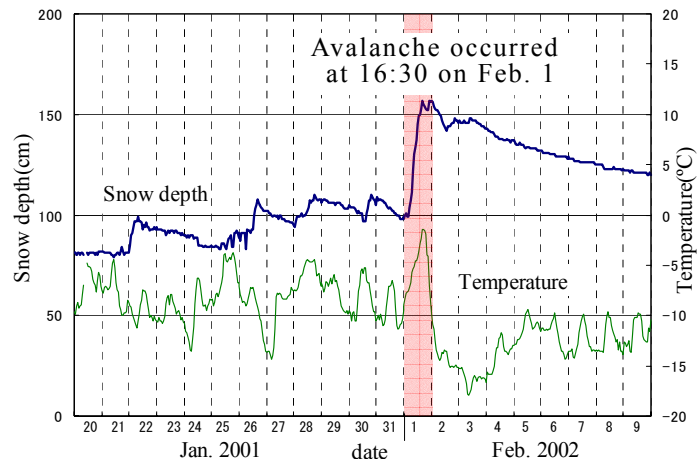
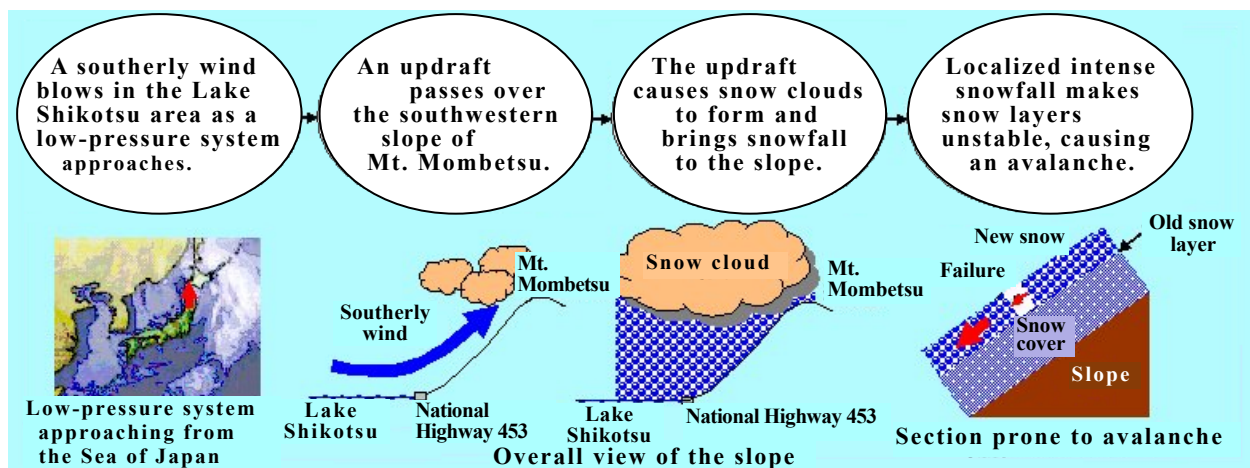Figure 2 Meteorological conditions around the time of avalanche

Figure 3 Schematic diagrams depicting the process of avalanche formation in the Lake Shikotsu area

Figure 3 is schematic diagram of meteorological changes and the avalanche formation process. It should be mentioned here that Lake Shikotsu is a caldera lake bordered on the southeast by Mt. Tarumae, on the northwest by Mt. Eniwa, and on the northeast by Mt. Mombetsu (the study area). Such topographical factors were considered to induce snow clouds and bring heavy snowfall, as Figure 3 illustrates.

4. Measures to determine the avalanche likelihood

A method of quantitatively forecasting avalanche likelihood was developed. It takes into account the abovementioned conditions of avalanche formation at Lake Shikotsu.

For meteorological factors, this study focuses on low-pressure system and snowfall amount as triggers for avalanche formation. Low-pressure system is an

indirect factor in snow cloud formation and heavy snowfall, depending on its movement and location. Amount of snowfall is a direct factor, as snow cover deepened by heavy snowfall induces avalanches.

4.1 Pressure gradient (*I*)

To determine a pressure gradient (*I*) around the Lake Shikotsu, hypothesized coordinates were structured, with four locations surrounding the lake (Figure 4) positioned on *x* and *y* coordinate axes and their atmospheric pressures positioned on the *z* coordinate axis. Kutchan, Tomakomai, Sapporo and Muroran were placed at (x_1, y_1, z_1), (x_2, y_2, z_2), (x_3, y_3, z_3) and (x_4, y_4, z_4) respectively.   The Tomakomai-to-Kutchan vector was expressed as $a(a_x, a_y, a_z) = (x_2-x_1, y_2-y_1, z_2-z_1)$ and the Sapporo-to-Muroran vector as $b(b_x, b_y, b_z) = (x_4-x_3, y_4-y_3, z_4-z_3)$.

Figure 4 Relative positions of Lake Shikotsu and barometric observatories

These two intersecting vectors determined the atmospheric pressure plane. A normal vector crossing the atmospheric pressure plane at right angles was derived from a vector product $a \times b$, and therefore,

$$a \times b = (a_y \cdot b_z - a_z \cdot b_y,\ a_z \cdot b_x - a_x \cdot b_z,\ a_x \cdot b_y - a_y \cdot b_x) \qquad \cdots (1)$$

Derived from *x* and *y* components of this normal vector, the direction of atmospheric depression, θ (clockwise, with north as 0°), can be expressed as follows:

$$\theta = 180° - tan^{-1}(Y / X) - 90°(X / |X|) \qquad \cdots (2)$$

where *X* and *Y* respectively represent *x* and *y* elements of the normal vector.

Then, the slope of the atmospheric pressure plane, or pressure gradient, was calculated from *x*, *y* and *z* components of the normal vector.

$$V = \sqrt{(X^2 + Y^2)} / Z \qquad \cdots (3)$$

where *Z* represents *z* components of the normal vector.

As several case studies have indicated that southerly winds in the Lake Shikotsu area induce avalanche, this study defined the pressure gradient (*I*) of a low-pressure system approaching from the west ($\theta = 270°$) as the index for avalanche prediction. *I* is defined in this paper as

$$I = V \cos(\theta - 270°) \qquad \cdots (4)$$

4.2 Stability index (*SI*)

To examine a method of determining the avalanche likelihood from heavy snowfall, the avalanche records collected from the Lake Shikotsu area were
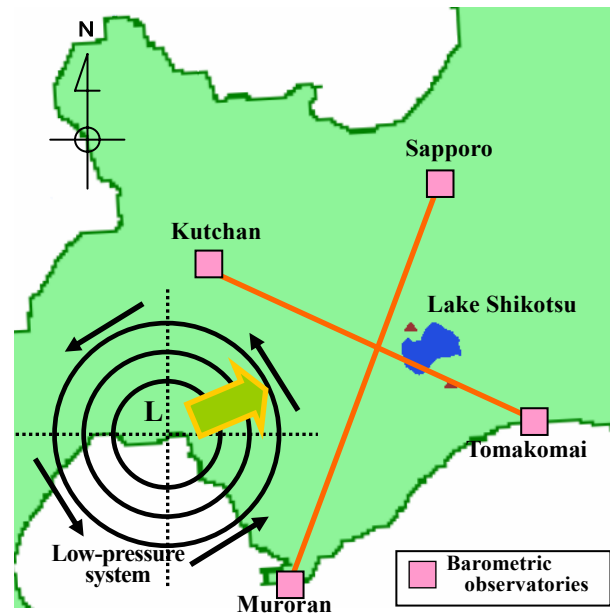
referred to.   It was hypothesized that in a surface avalanche a new snow layer accumulates on the surface of the previously accumulated snow, beginning at time ti, until it slides as an avalanche.

Base on previous studies on SI (Endo, Ozeki and Niwano (1990)[2], Endo (1993)[3] and Suizu (2002)[4], this study attempted to obtain the SI of the ti layer at time t.

SI is expressed using a shear stress τ (N/m^2), and a shear frame index SFI (N/m^2).   Therefore,

$SI = SFI / \tau$ $\cdot\cdot\cdot$ (5)

Here, for τ we can substitute snow load $W(t, ti)$ above the ti layer at time t.

$\tau = W(t,ti) \cdot g \cdot cos\theta \cdot sin\theta$ $\cdot\cdot\cdot$ (6)

where, W is snow load (N/m^2) and θ is slope angle. SFI is given by

$SFI = B \cdot \rho^{m}$ $\cdot\cdot\cdot$ (7)

where, ρ is snow density (kg/m^3) , B is the intercept of the power series equation that approximates the relationship between SFI and ρ, and m is the slope of that equation.

The snow density ρ, at time t, of a layer accumulated from time ti through t, can be derived from the equation for compressive viscosity coefficient of dry snow $\eta = C \cdot \rho^{n}$, and given as

$\rho(t, ti) = \{ ng /C \cdot cos^2\theta \cdot Q(t, ti) + \rho_0^{n} \}^{1/n}$ $\cdot\cdot\cdot$ (8)

where, ρ_0 is initial snow density (kg/m^3), $Q(t, ti)$ is cumulative snow load (N/m^2) obtained by integrating snow load above the ti layer from time ti to t, C is the intercept of the power series equation that approximates the relationship between η and ρ, and n is the slope of that equation.

To combine these equations, the SI of the ti layer at time t is expressed as

$$SI(t, ti) = \frac{B \{ng/C \cdot cos^2\theta \cdot Q(t, ti) + \rho_0^{n} \}^{m/n}}{W(t, ti) \cdot g \cdot cos\theta \cdot sin\theta} \qquad \cdot\cdot\cdot (9)$$

where the following values were substituted for the SFI-related coefficients B and m, and for the compressive viscosity coefficient (η) related coefficients C and n.

$B = 3.10 \times 10^{-4} N \cdot m^{-2} (kg/m^3)^{-m}$, $m = 3.08$

$C = 1.09 \times 10^{-4} N \cdot m^{-2} \cdot hr \cdot (kg/m^3)^{-n}$, $n = 4$

The slope angle θ of the section with avalanche was 45º and the initial snow density ρ_0 were defined by the following equation given by Suizu (2002)[4]:

$\rho_0 = 54$ (Ta(temperature) $\leqq$ 2ºC)

     $= 79 + 12.5 \cdot Ta$ (Ta(temperature) $\geqq$ 2ºC)

5. Determination and evaluation of the avalanche likelihood

The equations for pressure gradient (I) and stability index (SI) were applied to the ex-post forecast of an avalanche that occurred on February 1, 2001, and another on January 27, 2003.   Atmospheric pressure data used in this study were based on hourly data issued by the Japan Meteorological Agency.   The rate of snowfall (hourly increase in snow depth) and temperature were taken from hourly data of a road weather telemeter of the Hokkaido Development Bureau (at Kita-okuizari).

Figure 5 illustrates the analysis results for the avalanche on February 1, 2001, showing the relationship between avalanche occurrence time and pressure gradient (*I*). The pressure gradient (*I*) increased and exceeded the threshold value of I = 2.86 (minimum value of past avalanches) at 7:00, and the avalanche took place eight hours after *I* reached its maximum.
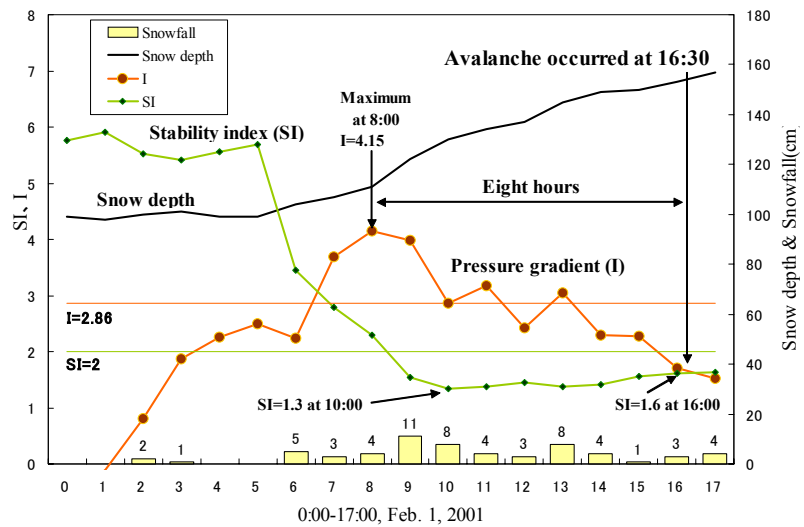

Figure 5 Changes in the risk factors before and after the avalanche of February 1, 2001

This suggests that that it may have been possible to forecast the avalanche. As for the stability index *SI*, starting from *SI* = 1.3 at 10:00, the *SI* remained below 1.5 until 14:00 (the reference value *SI* < 1.5 was quoted from Perla (1977)[5]). The *SI* was 1.6 around 16:30, at which time the avalanche was considered to have taken place; therefore, the forecast was not accurate perfectly. However, as it was possible to predict the likelihood of avalanche early enough for road management, the method's validity was verified by and large.

Figure 6 shows occurrence conditions of the avalanche on January 27, 2003. Similarly, the pressure gradient (*I*) increased and passed the 2.86 border at 13:00, and reached its maximum at 21:00. The avalanche took place two hours after the maximum was reached. The stability index (*SI*) fell below 1.5 after 19:00 and marked its minimum (1.1) at 23:00, which is the time avalanche occurred.
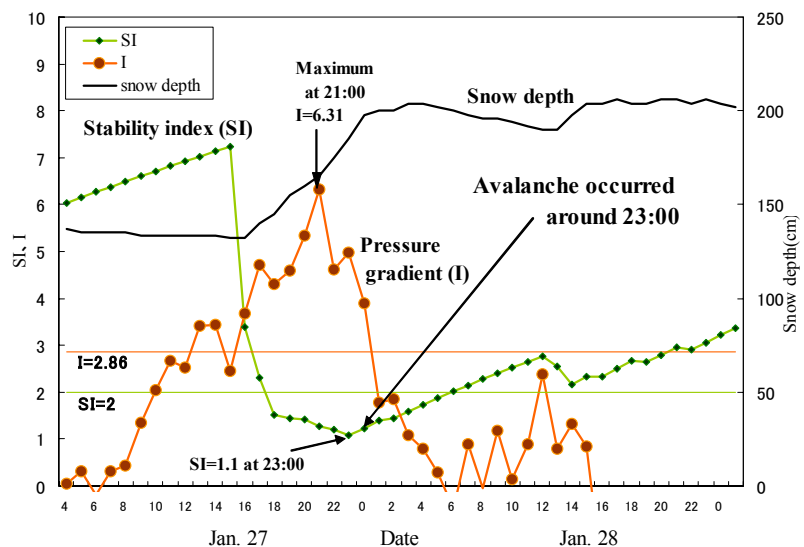

Figure 6 Changes in risk factors before and after the avalanche of January 27, 2003

The avalanche occurrence was forecast at each hour. Thus, the method developed in this study using pressure gradient and stability index is considered to be highly effective in evaluating the likelihood of surface avalanche induced by heavy snowfall at Lake Shikotsu.

6. Examination of assistance for road management

For better road management against avalanche, the following abilities must be developed.

1. The ability to predict likelihood of avalanche and conduct effective patrol.

2. The ability to predict the possibility of avalanche and determine the enforcement of traffic restrictions

3. The ability to predict reduced likelihood of avalanche and to determine the removal of traffic restrictions

In responding to the above requirements, keys to the effective application of this avalanche risk evaluation method are as follows. For the first item, examine the pressure gradient (I): Avalanche is likely to occur when I exceeds 2.86 (the minimum value in past avalanche records observed at Lake Shikotsu). For the second item, examine the stability index (SI): Avalanche is likely to occur when SI falls below 1.5. For the third item, consider the inverse result of the second item: Avalanche risk decreases when SI increases.

To establish a more effective management system, a criterion for each indicator should be set by taking these conditions into account. At this point, however, the draft of avalanche management criteria for the Lake Shikotsu area (Table 1) has set the pressure gradient at $I \geqq 2.86$ (based on the records of avalanche observed at Lake Shikotsu) and stability index has been set at $SI \leqq 2.0$ to allow for a margin of safety. Moreover, the snow depth H $\geqq$ 1 m was included as a third factor, and an attempt was made to integrate these three factors and apply them to road management. The appropriateness of these criteria needs to be verified.

The system will take advantage of data from the existing road weather telemeters used for road management; therefore, the installation of new facilities is not required.

Table 1   Avalanche management criteria for the Lake Shikotsu area（draft）

Management level	Factor		
	Snow depth (H)	Pressure gradient (I)	Stability index (SI)
I Caution	$H \geqq 1$m	—	—
II Warning	$H \geqq 1$m	$I \geqq 2.86$	
III Closure	$H \geqq 1$m		$SI \leqq 2.0$
Removal			$SI > 2.0$

7. Avalanche likelihood factor monitoring system

An avalanche monitoring system was designed in light of the abovementioned pressure gradient (I), stability index (SI) and management criteria (draft).

Figure 7 shows a website image of current avalanche likelihood and corresponding management level, changes in avalanche likelihood for the past 24 hours and diagrams of snow depth and other indicators. To briefly explain the

management levels, 1) "Normal" is displayed when the snow depth is less than 1 m and the avalanche likelihood is zero; 2) "Caution" is displayed in yellow at Likelihood I, which is when the snow depth exceeds 1 m; 3) "Warning" is displayed in orange at Likelihood II, which is when the pressure gradient (*I*) exceeds 2.86; 4) "Traffic Closure" is displayed in flashing red at Likelihood III, which is when the stability index (*SI*) falls below 2.0; and 5) "Traffic Closure" is removed when the stability index (*SI*) exceeds 2.0 and the management level returns to "Warning." This system is also capable of sending information by e-mail when "Traffic Closure" sign is issued.

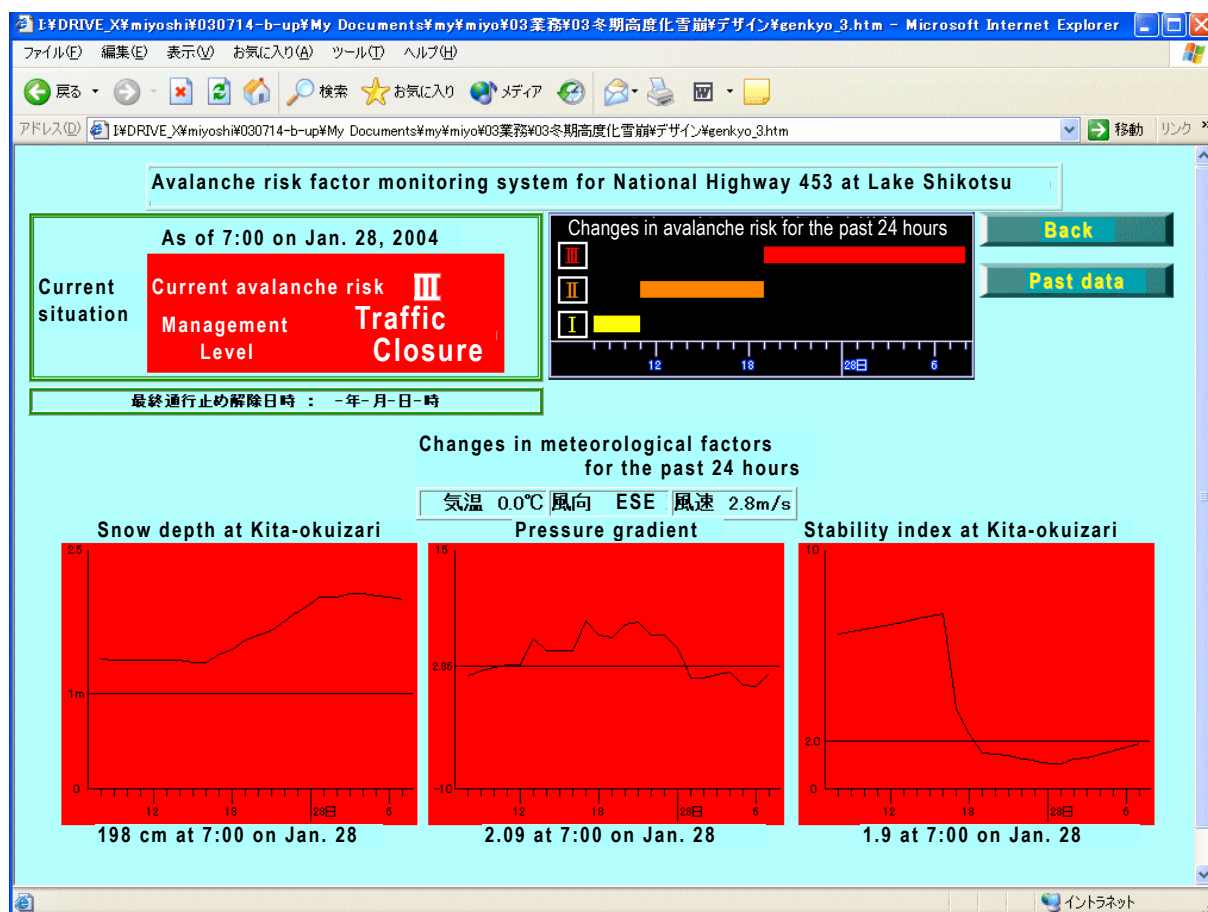
Figure 7 Display of Avalanche risk factor monitoring system

8. Conclusion

This study accomplished the following.

(1) The process of avalanche formation in the Lake Shikotsu area was understood.

(2) A method of hourly forecast for likelihood of surface avalanche induced by heavy snowfall in the Lake Shikotsu area was established, although with some limitations.

The following are issues to be addressed.

(1) As the examination was conducted using few avalanche records, more data need to be stored to enhance the analytical accuracy.

(2) The study should be further developed so that it can be applied to avalanches of different types and to other areas.

9. Postscript

It should be verified that the avalanche likelihood monitoring system that begun experimental operation is effective in improving road management and patrol systems, and in determining traffic restrictions.

Acknowledgements

References

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