

SPATIAL VARIABILITY OF SOME SNOW CHARACTERISTICS ON A SLOPE AND INTERPRETATION OF MEASUREMENTS FOR SNOW STABILITY ASSESSMENT

Pavel Chernous¹, Yuri Fedorenko², Nikolay Barashev¹

¹) Center for Avalanche Safety, "Apatit" JSC, 33a, 50-Years of October St., Kirovsk, Murmansk Region, 184250 Russia, e-mail: pchernous@apatit.com

²) Polar Geophysical Institute, Russian Academy of Sciences, 14, Fersmana St., Apatity, Murmansk Region, 184209 Russia

Snow thickness, density, shear strength and temperature are analyzed. Spatial distributions of the snow characteristics are considered as random fields and their variability is described statistically. The statistical parameters such as: mean values, standard deviations, coefficients of variability, estimations of the correlation and structural functions were obtained with data of numerous measurements in the Khibiny Mountains (beyond Polar Circle in Russia). The variability of the considered characteristics is very high due to unevenness of the underlying surface and redistribution of snow by wind. Comparison of the mentioned statistical parameters with ones obtained in the Tien Shan Mountains (Middle Asia) and other areas shows that spatial variability much higher and thus interpretation of measurements for avalanche or slushflow release forecasting more difficult in the Khibiny Mountains. Accuracy of the used methods of measurements was estimated by extrapolation of the empirical autocorrelation function to zero. There were also estimated errors of interpolation and substitution of mean integral values and mathematical expectations by mean arithmetical ones. Some questions concerning of the distribution of measuring networks in avalanche starting zones and interpretation of data obtained from them are considered. Approaches to the stochastic simulation of the fields of snow characteristics on mountain slopes and their using for evaluation of snow stability are suggested. The work was supported by Russian Foundation for Basic Research (grants: 04-05-65057-a and 05-05-64037-a).

Key words: snow characteristics spatial variability, accuracy estimations, measurements' interpretation, simulation.

It is widely known that such characteristics of snow as thickness, density, strength, temperature etc. have impact on mechanical stability of the snow on the slope and as well vary in the space and time. In particular, these characteristics can considerably vary in the points situated in small distances from each other. Such differences are the result of snow cover formation conditions. First of all, they depend on relief and micro-relief of underlying surface, precipitation as well as wind conditions, snow drifting, radiation, etc. All these factors in interaction create quite a variegated picture of thickness, density, strength and temperature values in the space. As a result deterministic description of these characteristics is impossible. That's why the following questions occur:

- 1) In which way it is possible to analyze measuring data in separate points for avalanche forecasting?
- 2) What measuring networks to choose in avalanche starting zones to provide avalanche forecast models with reliable data?

To answer these questions the following method of study the snow characteristics spatial structure has been used. Every field $f(x, y)$ is considered as random and random function theory is used for its description. Estimation of mathematical expectations m_f , variances s_f^2

and normalized autocorrelation functions $r_f(l)$ calculated with data of special snow surveying has been used in the research as characteristics of spatial statistic structure. The following criteria were chosen for placement of measuring sensors in avalanche starting zones.

1. Measuring network should provide data of required accuracy in any point of avalanche starting zone. Here method of interpolation in stochastic field has been considered. Using linear interpolation between adjoining measurements and its standard error as a degree of accuracy it is necessary to place measuring sensors in such a way that the standard error in any point of avalanche starting zone won't be higher some given value.

For linear interpolation in the center of a segment uniting two points of measurements (where the error is maximum), standard error is equal (Gandin and Kagan, 1976) to:

$$E_f^2(l) = e_f^2(l) s_f^2 \quad (1)$$

$$e_f^2(l) = \frac{\hat{e}^2 3}{2} - 2r(l) + \frac{1}{2}r(l) + \frac{1}{2}h^2 \quad (2)$$

Where

$e_f(l)$ - relative linear interpolation error

h - relative measuring error

$$h = \frac{D}{s_f} \quad (3)$$

D - standard error of measuring.

Solving the equations (1) and (2) relative to l , it is possible to calculate maximum interval between measuring points the interpolation error for which won't be higher of the given value. In some cases it is possible to use interpolation in the plane. Such interpolation accuracy can be characterized by error in the center of equilateral triangle, square or some other geometrical figure.

2. To estimate snow stability on the slope (especially in simplified models), slushflow formation (snow melting calculations), it is necessary to have data on snow characteristics relating not to separate points but to the whole area S or some part of it. For example, it is more important to know average value of snow thickness for the whole area rather than in separate points. In other words, it is necessary to estimate mean integral value

$$f_s = \frac{1}{S} \iint_S f(x, y) dx dy \quad (4)$$

where

$f(x, y)$ - true f -characteristic value in the point of avalanche starting zone with coordinates x, y .

Usually mean arithmetic is used as an estimation of mean integral value

$$\overline{f^l} = \frac{1}{n} \sum_{i=1}^n f_i^l \quad (5)$$

where f^l - measured f -characteristic value in the point with coordinates x, y and;

n - number of measurement points.

The following values are taken as accuracy indexes of the substitution.

$$F^2 = (\overline{f^l} - f_s)^2 \quad (6)$$

$$g^2 = \frac{F^2}{s_f^2} \quad (7)$$

Estimation $\overline{f^l}$ is better when $F^2(g^2)$ is less.

Beginning with accuracy of f_s the task of placement the measuring network can be solved with finding of such a number of measuring points and their positional relationship, where value $F^2(g^2)$ won't be higher of the predetermined level. Methods of estimation for fields with different statistic structure can be found in (Kagan, 1965). In case when field is random, homogeneous and isotropic and measuring errors are random, additive and non correlated with measuring value, in (Zhukovsky et al., 1976) was obtained general formula for g^2 .

3. Sometimes it is interesting to know mathematical expectation - m_f rather than its mean value in the limited area - S . If the arithmetic mean calculated on measurements in n points (5) is taken as estimation of the mathematical expectation - m_f then accuracy of a such substitution can be characterized with

$$P^2 = (\overline{f^l} - m_f)^2 \quad (8)$$

$$a^2 = \frac{P^2}{s_f^2} \quad (9)$$

When measuring error does not contain systematic constituent and uncorrelated with measured value, a^2 can be calculated with the following expression (Zhukovsky et al., 1976):

$$a^2 = \frac{1+h^2}{n} \hat{e}^2 + \frac{2}{n} \sum_{i < j} \frac{1}{1+h^2} r_f(l_{ij}) \quad (10)$$

Requirements to measuring network are similar to requirements formulated in paragraph 2, i.e. number of measurement points and their position have to guarantee that value of $P^2(a^2)$ won't be higher of a given one.

Permissible values $E^2, F^2, P^2(e^2, g^2, a^2)$ depend on a model used for snow stability assessment and requirements to accuracy of avalanche release forecasting.

Study results of the spatial statistic structure of the snow thickness, density, shear strength and

temperature for some types of snow in the Khibiny as well as accuracy characteristics for the various schemas of measuring network are presented below.

2. STUDY RESULTS

For the time consuming study of snow characteristics, excluding measurements of full snow cover thickness that turned to be relatively easy, obtained data concerns only top snow layer. As a rule, that was fresh snow blown by wind.

2.1 Snow cover thickness

It took 4 winter seasons of special snow survey to reveal characteristics of spatial statistical structure of snow cover thickness. Steepness of the slope in places of measurements varied from 15° to 35° . Rock debris with bedrock benches prominence was an underlying surface in the area of snow survey (the most characteristic surface for avalanche starting zones in the Khibiny). During the snow survey the full thickness of snow cover H and thickness of fresh drifting snow layer h has been measured.

For H measuring were conducted every 5 m and every 1 m, while measuring h . Part of measuring profiles was directed along the line of slope, other – in perpendicular direction, along horizontals. Measuring H was conducted with metallic probe, while h – with a ruler. (in the point of measurement a snow pit was dug out down the layer below fresh drifting snow). Measurement accuracy was 1 sm. The total number of measurements is more than 4000 in 37 profiles up to 1000 m in length for H and more than 4 500 in 13 profiles up to 400 m in length for h .

Average snow cover thickness in profiles varied from 0.1 to 1.5 m. Values changed between profiles, however quite a distinct dependence of standard deviation from mean snow cover thickness has been revealed. It increases with growing thickness, but becomes constant 0.3-0.4 m with average snow cover thickness ≥ 0.5 m.

Values of averaged in two mutually perpendicular directions correlation functions were calculated. There is practically no difference between them that allows consider snow cover thickness field H in a first approximation as isotropic.

Correlation function $r_H(l)$ averaged for all profiles is shown in the Figure1. $r_H(l)$ can be approximated by expressions:

$$r_H(l) = 0,9 \exp(-0,34l^{0,63}) \quad (11)$$

$$r_H(l) = 0,94[1 - (0,2l^{0,33})] \quad (12)$$

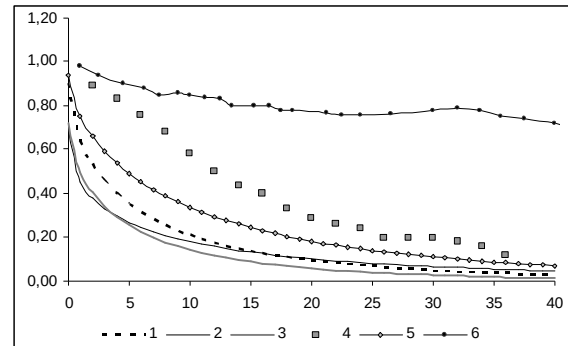


Figure 1. Curves that approximate empiric correlation functions of snow characteristics in avalanche starting zones:

- 1 – smoothed empiric correlation function for fresh drifting snow thickness - $r_h(l)$;
- 2 – smoothed empiric correlation function for fresh drifting snow density - $r_r(l)$;
- 3 – smoothed empiric correlation function for fresh drifting snow shear strength - $r_c(l)$;
- 4 – smoothed empiric correlation function for snow temperature at depth 20 cm;
- 5 – smoothed empiric correlation function for total snow thickness - $r_H(l)$;
- 6 – shear strength correlation function for new snow - $r_c(l)$. West Tyan-Shan. (Kanaev, 1969)

Expression (12) gives a poor approximation against (11); however, it allows using ready solutions for calculation of mean integral snow thickness error.

Snow thickness field is notable for the fact that correlation function in the interval 0-20m is decreasing by an order. In this range the structural function is increasing intensively (Figure 2). In comparison it is possible to take structural function of snow cover thickness, obtained in other geographical conditions (Chirkova, 1977) (Figure 2)

Structural function values are connected to correlation function values by the following expression: $B_f(l) = s_f^2[2 - r(l)]$

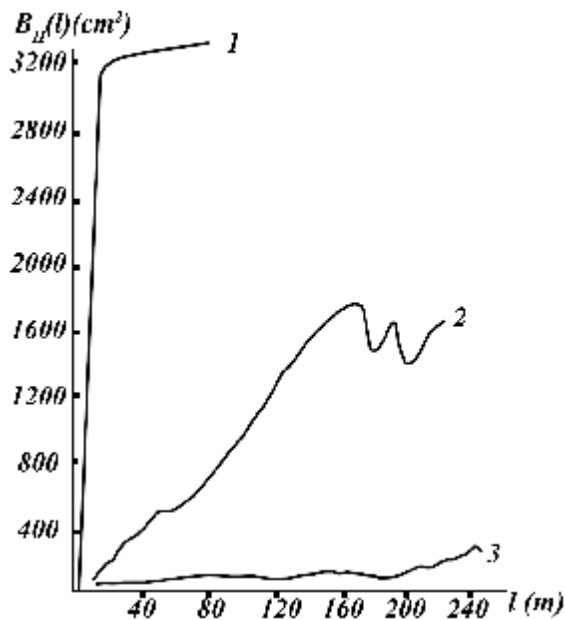


Figure 2. Empiric structural function of full snow cover thickness on the slopes (for the moment of maximum snow accumulation)
 1 – Khibiny
 2 – Kamchik pass region, West Tyan-Shan (Chirkova, 1977)
 3 – Dukant avalanche station, West Tyan-Shan (Chirkova, 1977)

Such a considerable value of obtained structural function in the area of saturation can be explained by two main reasons – inhomogeneous underlying surface (micro-relief) and intensive snowstorm activity.

Underlying surface in the area of snow survey, as it was mentioned above, is a rock debris with c bedrock benches prominence, while in the West Tyan-Shan it is smoothed and grass-covered slopes.

Snowstorm activity in other regions shown in the Figure 2 is quite weak in comparison with that in the Khibiny.

Obtained results show a great spatial irregularity of snow deposition in the Khibiny slopes. Snow thickness variance is rather high, correlation between thicknesses in separate slope points decreases sharply with increasing distance. It's natural that taking in account this fact and its quantitative characteristics, snow measuring network should be placed in avalanche starting zones and numerical simulation for estimation of snow mechanical stability on the slope should be carried out.

Values of linear interpolation error e_H in relation to measuring points intervals l and h were calculated according to expression (1). Obtained results are given in the Figure 3.

Values of interpolation error at values small h considerably depend on l . At large h , e_H depends on l weakly.

For existing snow measuring network in Centre of Avalanche Safety of "Apatit" JSC (CAS): $s_H=0.4$ m, $D_H=0.2$ m, $l=50$ m, $e_H=1.16$, $E_H=0.46$ m.

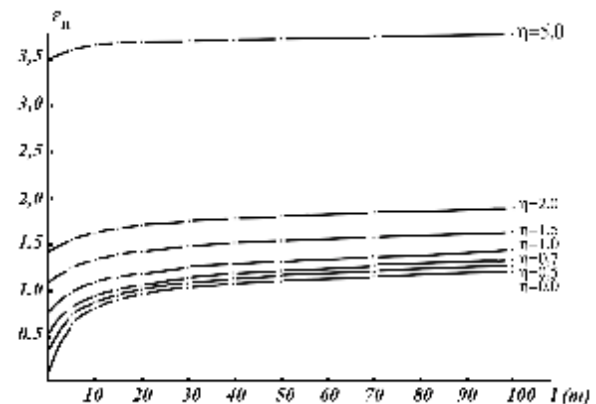


Figure 3. Dependence of linear interpolation error for snow cover thickness e_H from distance l between measuring points and different values h for the field with correlation function $r_H(l) = \exp(-0.22l^{0.67})$

It is evident that interpolation error is quite high and it is possible to make it less only by decreasing distance between snow stakes (even with absolutely accurate measurements interpolation error remains practically the same $E_H=0.44$ m)

To obtain interpolation accuracy, equal to measuring accuracy, i.e. $E_H=0.2$ m, $e_H=0.5$, the distance between snow stakes should be 1.5 m. It is obvious that it is impossible to construct snow measuring network for such a statistical structure of snow cover thickness, where linear interpolation error will be less, than s_H . As calculations show, change from interpolation along the segment to interpolation on the plane (interpolation errors in the center of equilateral triangle and in the centre of square with side - l were calculated) insignificantly increases the accuracy of interpolation.

Relative errors of substitution of the mean integral by the arithmetic mean g_H^2 were calculated for the case when all area is divided into n equivalent squares with side $\sqrt{S/n}$ for the field with correlation function (12) (Zhukovsky et al., 1976).

$$g_H^2 = \frac{h^2}{n} + (0,02\sqrt{S})^{0,33} \frac{1}{n^{1,16}} \quad (13)$$

Calculation results with (13) were tabulated. The table gives a clear view on the number of snow stakes, required to provide necessary accuracy of mean integral snow cover thickness in any avalanche starting zone or its part. It is possible to evaluate representativity of measurements with a separate snow stake. E.g. for an area $10 \times 10 \text{ m}^2$, snow thickness measured in the center of it will be different from average integral snow thickness not more than $F_H = s_H \times 0.80$

with probability 0.68. For $s_H = 0.4 \text{ m}$, $F_H = 0.32 \text{ m}$. Increasing probability of presence of the true mean integral value in some interval (confidence level should be high enough) results in increasing interval itself. Therefore, with probability 0.997 the interval value is 0.96m, i.e. relative error with average snow thickness 1 m will be about 100 %. It is evident, that error in calculating of snow volume in the avalanche starting zone according to the snow measuring network will be the same or even more.

Increasing number of measuring points will result in increasing accuracy for mean integral value of snow cover thickness.

Relative error of substitution mathematical expectation by arithmetic mean was calculated for equidistant measuring points, set on the straight line with length L . In this case expression (10) transformed to the following one:

$$a^2 = \frac{1 + h^2}{n} \cdot \left(\frac{1}{n} + 2 \sum_{k=1}^{n-1} \frac{k}{n} \frac{1}{1 + h^2} r_H \frac{L \times k}{n - 1} \right) \quad (14)$$

Values for snow measuring profiles, used in CAS in the Khibiny (with length up to 400 m) with snow stakes every 30-50 m, can be calculated with formula for non correlated measurements:

$$a^2 = \frac{1 + h^2}{n} \quad (15)$$

Value difference between a , calculated according to formula (14), (15) in the Khibiny conditions is less than 13%. Mathematical expectation error P is 0.2 m for snow thickness measurements in a 200-m profile, containing 5 snow stakes in every 50 m. To increase accuracy m_h twice as much, the number of snow stakes in profile should be increased in an order. Although there is a limiting error for a length L . Further accuracy increasing is possible only due to profile length increase that is not always possible because of limited size of the homogeneous parts of an avalanche starting zone and the starting zone itself.

Obtained error estimation is appropriate to the Khibiny conditions and CAS methods of getting data on snow thickness. It is clearly seen that accuracy is not high. The main reason to it is in snow deposition irregularity in the Khibiny slopes. Low accuracy of CAS measuring method has its impact too (snow stake has the least division 0.5 m, readings are conducted with binoculars).

E.g. using the method of CAS for snow thickness measurement in the region of avalanche station Dukant in the West Tyan-Shan, interpolation error in the center of segment (length 50 m) would be $E_H = 0.15 \text{ m}$ (in the Khibiny - 0.46) using more accurate measuring (with the least division 0.05 m), as it is done at Dunkant station, the value decreases till $E_H = 0.05 \text{ m}$.

It is obvious, that using similar methods to obtain data on snow thickness in separate points of avalanche starting zones for avalanche forecast, the result will be more successful in the Middle Asia mountains than in the Khibiny.

It is clearly seen from (13) and (14) that estimation accuracy of H_s and m_H is higher with increasing number of measurements, but it is difficult to set a great number of snow stakes. The solution is in finding of new methods of measurements, e.g. photogrammetric or laser survey. Even being less accurate in thickness measuring at separate point it allows to make measurements in a big number of points and obtain more accurate estimation H_s and m_H .

All mentioned above also concerns of total snow cover thickness.

As study showed, the statistical structure of top snow layer thickness h in the Khibiny is quite similar to field structure of total snow cover

thickness. Figure 2 contains empirical correlation function of fresh drifting snow thickness, it is a result of smoothing of averaged correlation function, calculated for 13 profiles.

$$r_h(l) = 0,9 \exp(-0,34l^{0,63}) \quad (16)$$

Mean values of fresh drifting snow thickness varied from 0.04 to 0.23m, values s_h from 0.04 to 0.16 m, variation coefficient c_v from 0.1 to 1.4.

There is no data on spatial variability h in other mountain regions. In comparison, variation coefficients for new snow in the same range of mean thickness varied from 0.05 to 0.15 (data from Dunkant avalanche station in the West Tyan-Shan (Kanaev, 1975).

Values s_h are less similar ones s_H though equal m_h and m_H . The reason to it is that irregularity of avalanche starting zone ground micro-relief is more than irregularity of old snow surface micro-relief where fresh drifting snow is deposited.

In some cases, (when fresh drifting snow formation happens on the even surface of old snow with no dunes, and other wind-borne forms of snow micro-relief and under weak wind) thickness variance can be small ($s_h = 0,04 - 0,07$ m) even if m_h is high. Increasing mean thickness will lead to increasing standard deviation, although this correlation is weaker than for total snow thickness. Obtained data on statistical structure h allow to estimate error values $E_h^2, F_h^2, P_h^2(e_h^2, g_h^2, a_h^2)$, gained with different measuring sensor placement plans (to measure fresh drifting snow).

Linear interpolation relative errors for the field h are higher (but not more than 18%) than similar ones for H , but since s_H is considerably higher of s_h , absolute errors of linear interpolation are higher for field H (even with regards of that $D_h > D_H$, when snow thickness increase is calculated as difference of two consequent total snow thickness readings).

As it was done for H , to use ready solution (Zhukovsky et al., 1976) for approximation of empiric correlation function besides exponential (16), the following power dependence has been used:

$$r_h(l) = 0.9[1 - (-0.05l)^{0.38}] \quad (17)$$

Relative errors g_h for fields with a such correlation function were calculated. Though g_h values higher than g_H , in practice with $s_h < s_H$, absolute errors of F averaged for both cases turned out to be approximately equal. Relative errors F_h / h_s are often higher than similar F_H / H_s .

Relative error a_h is similar to a_H (difference is not more than 20 %).

As it is for H with placement of h -sensors in profiles every 30-50 m and more, a_h values can be calculated with expression (15) for non-correlated measurements. At the same time, however, it is important to keep in mind that h error for H is in 2-2.5 times less than similar for h (for snow stakes measurements).

With spatial variability of snow cover thickness to obtain equal accuracy of snow thickness data in avalanche starting zones in various physical-geographical conditions, measurement network should be different.

In practice to obtain relative error F_H / h_s and P_h / m_h , equal to F_H / H_s and P_H / m_H respectively (the most important characteristics of accuracy in stability models and snow accumulation estimation), the number of snow stakes used to calculate snow thickness increment should be 10-25 times more than that used to total snow thickness.

As both snow thickness increment and total snow thickness are measured with the same snow stakes, planning of snow measuring network should be near to given accuracy for h characteristics (h_s, m_h) that will lead to higher accuracy for analogous H characteristics.

2.2 Snow density

It took 3 winter seasons to measure top snow layer density r . The measurements were done with duralumin densimeter in the shape of a cylinder ($\varnothing=52$ mm, $h=240$ mm) and laboratory dynamometer with scale of 4 N, calibrated in density values with the least division equal to 0.02g/cm^3 . As it was done for snow thickness, density has been measured in two mutually perpendicular directions - along horizontals and along the line of slope and on the same slopes. The distance between measuring points in

profiles varied from 0.3 to 1.0 m. The total number of measurements was 2000.

Average density of fresh drifting snow in separate series of measurements varied from 0.18 g/cm³ to 0.27 g/cm³, variation coefficients 0.05-0.17. Any dependence between mean density and standard deviation hasn't been revealed. Values of empiric correlation function of fresh drifting snow density taking averaged of all profiles have been approximated by exponential (Figure 2) and power dependences:

$$r_r(l) = 0,7 \exp(-0,43l^{0,50}) \quad (18)$$

$$r_r(l) = 0,7[1 - (0,03l)^{0,29}] \quad (19)$$

It is clearly seen from Figure 2, that at small l , values of empiric correlation function are far from being equal to one, it is a result of measurement errors. Even in perfect laboratory conditions accuracy of measuring density is not higher than 0.01 g/cm³. In the field study it is lower. Errors in measuring can occur for various reasons (connected with snow stick on densitometer, partial load of densitometer)

Extrapolation of empiric correlation function values to zero shows that value of superior limit of standard error is approximately $0.5s_r$ and it ranges through 0.005-0.02 g/cm³.

As it is true for snow cover thickness, correlation in density field decreases sharply with increasing distance between measuring points. Maximum decrease of correlation function is in $0 < l < 5$ m range.

There is no data on spatial correlation or structural functions of snow density in avalanche starting zones obtained in other areas. It becomes evident in comparison of variations coefficients (c_v) of some types of snow, obtained in the West Tyan-Shan and Elbrus (Voitkovsky et al., 1986) with ones for fresh drifting snow in the Khibiny, that spatial variability in the Khibiny is quite high.

Linear interpolation errors e_r in dependence with distance l between measuring points and h , calculated according to (1), are the same to the values, obtained for fresh drifting snow thickness (maximum difference is 7%)

To provide interpolation accuracy equal to measuring accuracy, i.e. $E_r = D_r = 0.01$ g/cm³, $e_r = 0.5$ the distance between measuring points should be about 1 m. It is obvious that really

possible to get interpolation error E_r no less than s_r , at the same time relative error E_r / r , will be small.

Relative errors of substitution of the mean integral by the arithmetic mean were calculated in the same way as for snow thickness. In the range 100-3000 m² error varies slightly and decreases by an order with growing number of measurements by two orders. Values of standard errors F_r in practice equal to s_r , i.e.

0.01-0.04 g/cm³. Measuring snow density in the same points as for snow thickness, relative error F_r / r_s in 6-50 times less than the same for snow thickness F_h / h_s .

Relative errors of substitution mathematical expectation by arithmetic mean a_r is close to the same ones for fresh drifting snow thickness (measuring r in n equidistant points of profile with length L).

Having variation coefficient of fresh drifting snow density less than variation coefficient for snow thickness in practice relative errors P_r / m_r even for two density measurements will be less, than fresh drifting snow thickness errors P_h / m_h in existing snow measuring profiles (10 measuring points).

Relative error $P_r / m_r \leq 0.1$ can be reached in 4-5 density measurements in profile with length 50-100 m. for profiles of density measurement with points every 30-50 m values can be calculated according to the following formula for non-correlated measurements (15).

2.3 Snow shear strength

Measurements to evaluate spatial statistic structure of snow shear strength were carried out during 3 winter seasons. The measurements were conducted with frame of 10x10 cm² and dynamometer. The total number of measurements in fresh drifting snow on the same slopes as for thickness and density, carried out in 10 profiles, were more than 1000. Measurement took place every 1 m. Mean values of C in series of measurements varied from 196 Pa for slightly packed snow to 3041 Pa for clearly seen snow slab. Standard deviation is varied within 80 – 690 Pa, variation coefficient within 0.06-0.86. Obtained estimation of correlation function in separate profiles varied

considerably. To get more reliable characteristics of $\mathbf{C}$ -field structure, all correlation functions were taken averaged, then smoothed by exponential and power functions:

$$r_c(l) = 0,72 \exp(-0,37l^{0,64}) \quad (20)$$

$$r_c(l) = 0,72[1 - (0,05l)^{0,40}] \quad (21)$$

Smoothed empiric correlation function $r_c(l)$ is shown in the Figure 2.

Obtained data reveals the fact that spatial variability of $\mathbf{C}$ for fresh drifting snow in the Khibiny is high. In comparison, values c_v , obtained in the west Tyan-Shan for new snow (Kanaev, 1969) are in the range 0,07 – 0,44. Besides, only in 4 measurement series of 33 the values c_v turned to be more than 0.25. Data from research reveals (Kanaev, 1969) (Figure 2) close correlation between $\mathbf{C}$ in new snow in different points located even in big distances. In fresh drifting snow, correlation decreases with distance sharply.

Values of extrapolation of empiric correlation function to zero shows that value of maximum of standard measurement error of $\mathbf{C}$ in fresh drifting snow is about $0.5 s_c$ and ranges from 39 to 343 Pa.

The majority of variation coefficients in $\mathbf{C}$ -measurement series varied 0.23-0.33. As variation coefficients for shear strength in 2-4 times greater than ones for density, relative measurement error of snow strength measuring method in 2-4 times greater than that for snow density.

Correlation function $r_c(l)$ only slightly differs from correlation functions $r_h(l)$ and $r_r(l)$ and its true as they are under the influence of the same reasons (like underlying surface and wind).

Linear interpolation error e_c in dependence with distance between measuring points l and values h calculated according to (1), is close to similar errors h (maximum difference is 3%)

The simplest and quite accurate estimation for linear interpolation in the field $\mathbf{C}$ is s_c . Relative errors $e_c / \bar{c}$ for snow shear strength in 2-4 times higher than for density. Relative errors of substitution of the mean integral by the arithmetic mean g_c is similar to g_h (maximum

difference is 2%). Relative errors F_c / c_s in mentioned measuring sensor placement plans in 2-4 times higher than density errors F_r / r_s and 4-8 times less than for fresh drifting snow thickness F_h / h_s .

a_c -errors for shear strength measuring in profile of L length in equidistant points practically coincide with similar ones for fresh drifting snow thickness. Difference in errors P_c / m_c and P_h / m_h , P_r / m_r is the same as in mentioned above F_c / c_s and F_h / h_s , F_r / m_r .

In measuring every 30-50m it is possible to use formula for non-correlated measurements.

Reliability of c_s and m_c , characteristics obtained on data in one snow pit is low and can lead to incorrect estimation of fresh drifting snow stability on the slope. High accuracy of m_c

($P_c / m_c < 0.1$) can be reached with some dozens of measurements in a profile of a few hundred meters length.

2.4 Temperature

Snow temperature measurements were conducted with electronic thermometer (measurement error $\pm 0.05^\circ\text{C}$) at depths 10 and 20 cm in a top layer of small-grained snow. Measurements took place in the mutually perpendicular directions along horizontal and along the line of slope. The distance between measuring points in profiles was 2 m.

The total number of measurements was 440. Average snow temperature values in the profile along the line of slope were -6.0° , -6.3° and in horizontal profile -3.4° and -5.5° at depths 10 and 20 cm. respectively. Corresponding standard deviations were equal 1.2, 0.7 and 0.4, 0.5 and variation coefficients -0.2, -0.1 and -0.1, -0.1. Obtained values of correlation function for temperature at different depths and profiles varied. To get smoothed averaged correlation function, as it was done for other snow characteristics, obtained data were not enough. Estimations of correlation function $r_t(l)$ are shown in Figure 2. Now, at least, possible to say that snow temperature is less spatially variable characteristic amongst considered.

3. SIMULATION OF SPATIAL DISTRIBUTIONS OF SNOW CHARACTERISTICS ON A SLOPE.

Since there is no precise knowledge of snow characteristics controlling snow stability it is impossible to get accurate conclusion on avalanche release possibility. It may sense to speak only about avalanche release probability. The data to reconstruct multivariate probability distribution of snow instabilities are unavailable. However, it may be worth to estimate it with a reliable deterministic model for evaluation of snow stability, describing its variables as random functions. For example snow stability can be described with stability factor:

$$F = \frac{c + frhg \cos a}{rhg \sin a} \quad (22)$$

In general the only way to obtain probability density p_F for arbitrary p_r , p_h , p_c and p_a is a Monte-Carlo simulation. This approach was used (Chernouss, 1994, Chernouss and Fedorenko, 1998) to estimate spatial distribution of avalanche release probability. This way is computationally intensive but hardly unavoidable, especially if it is necessary to use experimentally obtained probability densities of the variables which do not belong to the theoretical distributions. A technology of generating realizations of the snow characteristic random fields with given spatial statistical structure was described in (Chernouss and Fedorenko, 1998). Some examples of generated fields of H , r and c as well as a stability factor F are presented in Figures 4, 5, 6.

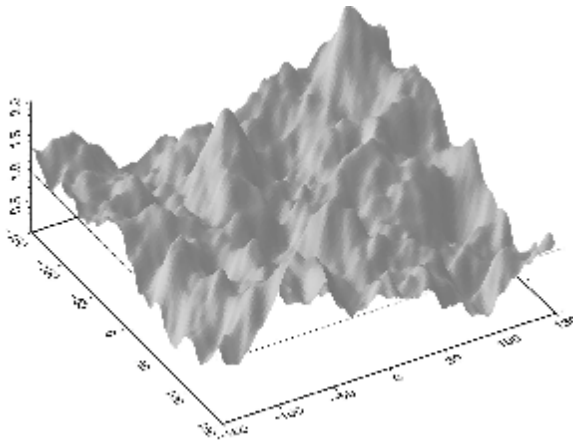


Figure 4. An example of a snow thickness distribution, generated with Monte Carlo method. $m_H = 1$ m, $s_H = 0.4$ m. Slope area 300×300 m².

4. CONCLUDING REMARKS

Obtained data on spatial statistic structure of snow characteristics in avalanche starting zones allow to do the following conclusions.

- spatial variability of thickness, density and

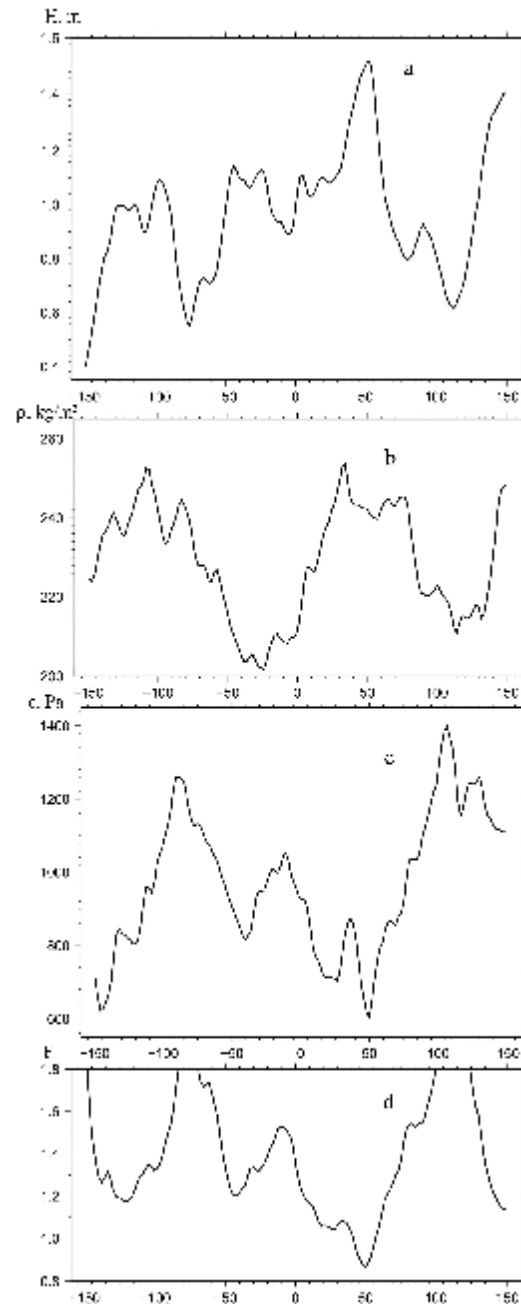


Figure 5. An example of snow characteristic distribution along the slope profile. a – snow thickness; b – density; c – shear strength; d – stability factor.

shear strength for fresh drifting snow in the

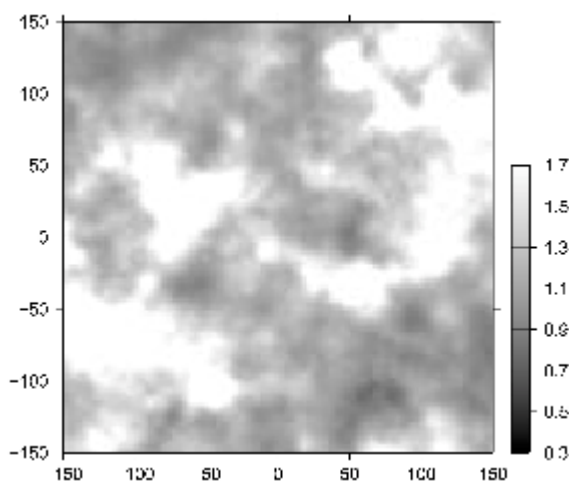


Figure 6. An example of a stability factor spatial distribution, generated with Monte Carlo method. Slope inclination -35° , $f = 0.4$, $m_H = 1$ m, $s_H = 0.4$ m, $r = 250$ kg/m³, $s_r = 30$ kg/m³, $c = 1000$ Pa, $s_c = 200$ Pa. Slope area 300×300 m².

Khibiny is high and considerably exceed spatial variability of these characteristics for top snow layer in other regions as Caucasus and Tyan-Shan.

- statistical structure h, r, c for fresh drifting snow is approximately the same. The most variable is fresh drifting snow thickness, and then comes snow shear strength and density. It is important for fresh drifting snow stability models;

- h, r, c for fresh drifting snow are mutually non-correlated, but it was found high correlation between t and r ($r_{tr} = -0.63 \dots -0.89$).

- it is appropriate to use non-traditional methods to obtain information about snow as photogrammetric or laser survey, penetrational-shear methods, etc. rather than data gained in labour-consuming snow-pit with conventional methods. The choice of measurement amount and areas should be made with regards of spatial variability of measured parameters and required accuracy for these values. Obtained for the first time estimations of error e, g, a for fresh drifting snow in dependence of measuring plans in avalanche starting zones allow to do that;

- to obtain necessary accuracy for snow stability on the slope, measuring sensor networks in various physical-geographical conditions should be different;

- linear interpolation error of thickness and physical-mechanical characteristics of snow in space is quite high and in practice equal to standard deviation of the parameter and can be even more. Therefore linear interpolation appliance to obtained data in places with no measurements (as for thickness and density of fresh drifting snow) and its further use in deterministic models can lead to gross errors in snow stability estimation.

REFERENCES

- Chernouss P., 1994: Statistical modeling of snow cover stability in mountain slopes. Proceedings of the International Snow Science Workshop, 6-10 October 1994, Snowbird, Utah, AAAP, Snowbird, p.341-345.
- Chernouss, P. and Fedorenko, Yu., 1998: Probabilistic Evaluation of Snow Slab Stability on Mountain Slopes. *Annals Glaciology*, v. 26, Cambridge, UK.
- Chirkova A.A., 1977: Peculiarities of structural functions of depth in dependence with avalanche starting zones relief. - Tr.SARNIGMI, issue37 (118), p.43-50. (in Russian).
- Gandin L.S., Kagan R. L., 1976: Statistic method of meteorology data analysis. Leningrad, GIMIZ, 360 p. (in Russian).
- Kagan R.L., 1965: Accuracy in calculating average throughout the square according to point measuring data. - Rt.GGO, issue 175, p.117-131. (in Russian).
- Kanaev L.A., 1969: Variation of snow characteristics. - Tr. SARNIGMI, issue 44 (59), p.25-42. (in Russian).
- Zhukovsky E.B., Kiseleva T.L., Mandelshtam S.M., 1976: Statistical analysis of stochastic processes Leningrad, GIMIZ, 408 p. (in Russian).