Application of empirical calculations and dynamics models for snow avalanche hazard assessment in Russia

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ABSTRACT: A lot of statistical runout models based on topographic parameters of the avalanche tracks were performed by snow engineers for different mountain regions of Russia. The main goal of our investigation was to test the capabilities of Russian empirical methods and Swiss avalanche dynamics program RAMMS to back-calculate well-documented avalanches (with volumes from 2 000 up to 2 100 000 m^3) in Russia. The most accurate information from powder and wet snow avalanches, extreme rare but also the frequent small ones is collected from 1960^{th} up today in the Khibini Mountains and in the Caucasus. It was digitized and put to the detailed large-scale digital avalanche database (GIS) with more than 50 years of observations for certain avalanche tracks. GIS was used to analyze the initial conditions of avalanches and model input parameters as well as to compare measured parameters with model results. GIS is a unique source of information for investigation avalanche flow rheology and calibration avalanche dynamics models. A new statistical approach for the assessment of the avalanche runout distance return period based on the avalanche paths clustering was developed using these data. We applied RAMMS to simulate more than 50 well-documented avalanche events and discuss the calibration of the avalanche model friction coefficients. Avalanche zoning is not yet used by land planning authorities in our country. Our results can be used for the future development of it in Russia.

KEYWORDS: snow avalanche, statistical runout models, dynamics modeling, RAMMS, hazard assessment

1 INTRODUCTION

After the decay of the USSR Russian Mountain regions became attractive for capital investments and more popular among tourists from all over the World. At the same time avalanche zoning is not yet used by land planning authorities to prevent building in avalanche hazard areas. As a result buildings are being constructed in areas that are endangered by snow avalanches. We argue that avalanche zoning will complement Russian snow engineering practice which is based on the complex avalanche hazard assessment.

The estimation of extreme avalanche runout distances, velocities, impact pressures and volumes is an essential part of avalanche hazard assessment in our country. Avalanche models have been developed in the former USSR and then in Russia since 1935. Unfortunately, the important work in the avalanche science done in our country was not well-known in the West, despite the fact that the first avalanche model (Kozik, 1962) was most probably developed by scientists in the USSR (Salm, 2004). Most achievements in Russian avalanche dynamics and hazard assessment were made between 1960 and 1990. Then most of research works were stopped due to the financial difficulties. Avalanche hazard assessment is still based on the results obtained from the simplest Russian avalanche dynamics and statistical runout models. Moreover, the calculations are still performed manually, without special software.

Russian Guidelines (SNIP 22-02-2003) are not clearly presented concerning avalanche dynamics parameters calculation. The application of any avalanche model as well as approach for estimation of its input parameters is accepted. Consequently different teams of engineers in Russia apply various dynamics and statistical models for avalanche hazard assessment. This gives more freedom to the practitioners but also causes a lot of troubles. In many cases it is not possible to apply commonly accepted Russian methods (Kozik, 1962; VSN 02-73; etc.) for a certain avalanche track for avalanche hazard assessment needs and the implementation of avalanche zoning due to poor historical events

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data availability, lack of possibilities to obtain the required field data, etc.

Therefore the values of the calculated parameters are rather uncertain. This is absolutely unallowable for the engineering practice. The motivation of this research was to reduce these uncertainties as much as possible.

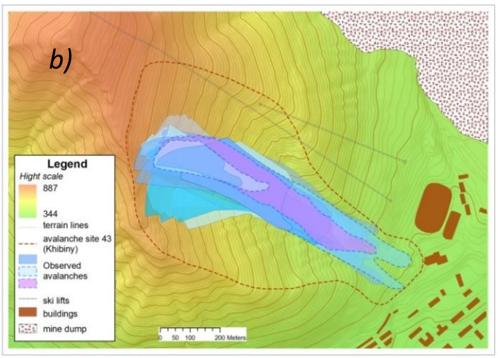
On the other hand, avalanche dynamics models of Voellmy-Salm or VS (Voellmy, 1955; Salm, 1966) and PCM (Perla et al., 1980) simple to use and well-liked by practitioners in the West and avalanche dynamics programs (AVAL-1D, RAMMS and others) as well as Alpha-Beta model (Lied and Bakkehoi, 1980) are not yet applied in Russian snow engineering practice. The main goal of our investigation was to test the capabilities of different statistical runout models (developed in Russia) as well as Swiss avalanche dynamics program RAMMS to back-calculate well-documented avalanches (with volumes from 2 000 up to 2 100 000 m^3) in Russia. We also try to discuss the calibration of the avalanche model friction coefficients as a function of the geographical characteristics of Russian mountain regions.

Avalanche hazard assessment in our country was based on the calculation of the extreme avalanche runout distances without reference to their return period. Several researches were made to find out the substantial method for the return period estimation in Russia (Blagoveshenskiy, 1991; Bozhinskiy et al., 2009 and others). In the present paper we develop a new statistical approach for the estimation of the runout distances return period.

2. ANALASIS OF PAST AVALANCHE EVENTS USING GIS

The first step of our investigation was the detailed analysis of past avalanche events. Systematic recordings of avalanches in our country started in 1970th. The results of such work were presented in the series of the inventory of snow avalanches of the USSR (Kadastr lavin SSSR [Inventory of the avalanches of the USSR]. Vol. 1–20, 1984–1991). The inventory is divided on issues, each dealing with certain time period of observations and specific mountain region.

The most accurate and well-documented data from powder and wet avalanches, as well as extreme rare and frequent small ones is collected from 1960th up today in the Khibini Mountains (northwest of Russia, the Kola Peninsula) by the Avalanche Safety Center (ASC) and in the Caucasus (The Mt. Elbrus region) by the Geographical Faculty of the Lomonosov Moscow State University. Seven avalanche test sites in the Khibini Mountains (Kirovsk surroundings) and nineteen in the Caucasus were considered and extensively analyzed. An almost complete avalanche dataset since the beginning of observations in the Khibini Mountains exists. For most of the avalanches exists a detailed description of the release zone and the fracture snow height; avalanche deposits (with debris height measurements); weather conditions during and before the release (including temperatures and the precipitation); snow pits on the release fracture; photos; etc. The detailed description of the extreme catastrophic avalanches with volumes up to 2 100 000 m^3 exists in the Caucasus. Each observed avalanche in both regions was marked on a large scale (1:5 000) paper map, contour line interval 5 m. These historical data was stored in a large scale digital avalanche database which was used for the development of GIS «Snow Avalanches of Russia» (Figure 1) which is permanently updated for other avalanche sites. This database was used to analyze the initial conditions of avalanches, model input parameters as well as to compare measured runout distances, velocities with model results.



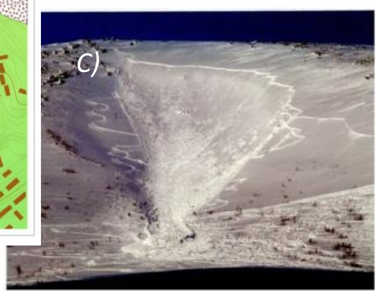


Figure 1. An example: *a)* Test site № 43, ASC numeration (photo courtesy of Marina Vikulina); *b)* The layout of observed avalanches in the test sites № 43; *c)* One of the observed avalanches in 43 test site (photo courtesy of ASC).

3 STATISTICAL RUNOUT MODELS FOR AVALANCHE HAZARD ASSESSMENT

Statistical avalanche models are widely used in Russian avalanche hazard assessment practice because of their simplicity. Most of them are based on the long-term observation of extreme avalanche runout distances or vegetation data in a certain mountain region (The Khibini, Caucasus or Zailiyskiy Alatau mountains) or in a group of mountain regions (for example, Khibini, Caucasus and Swiss Alps). However, most of them are regional (Akkuratov, 1961; Blagoveshenskiy, 1991; etc). After the publication of Kozik (Kozik, 1962) most of Soviet and then Russian scientists started to apply the average coefficient of friction f, defined by

$$f = H/L = \tan(\alpha) \quad (1)$$

with H the height, L the horizontal distance, and α the average slope angle of the avalanche path. S.M. Kozik (1962) suggested the use of a graphical method and recommended f_{min} = 0,3 (α = 16,7° the critical slope angle) for an estimation of the «maximum» avalanche runout distances and calculation of their velocities. His method is still widely used by practitioners, for example it was applied for the avalanche hazard assessment posed to Olympic constructions in the Krasnaya Polyana, Sochi (Kazakov et al., 2012).

The dependences of f_{min} and L on the topographic parameters as well as on the fracture snow height (Table 1) were obtained by several Russian scientists.

We applied well-known statistical models (Table 1) for the extreme avalanche runout distance calculation in the Khibini Mountains for all the considered test sites. The characteristics of large potential avalanche release areas were used for the calculations, because we were looking for extreme runout distances. Analyzing the avalanche database, it was detected that real avalanches since 1960th never started at the same time from the whole area. The outputs (Figure 2) using different statistical runout models differ significantly, sometimes even more than twice. Since 1960th actual avalanches of two sites ran farther than the calculated "maximum" distance.

Table 1. The dependences of the runout distance on the initial conditions of avalanches.

Parameters / Authors	Area of the release zone	Mean slope angle of the release zone	Mean slope angle of the path	Avalanche volume	Avalanche mass	Avalanche potential energy	Fracture snow height
Akkuratov,1961				✓			
Blagoveshensky, 1973	✓	✓					
Severskiy, 1978 (1)					✓		
Severskiy, 1978 (2)						✓	
Zalihanov, Runich 1978	✓		✓				
Zolotarev, 1981			✓				
Moskalev, Efimov, 1972	✓						
Ebralidze, 1990	✓		✓				✓

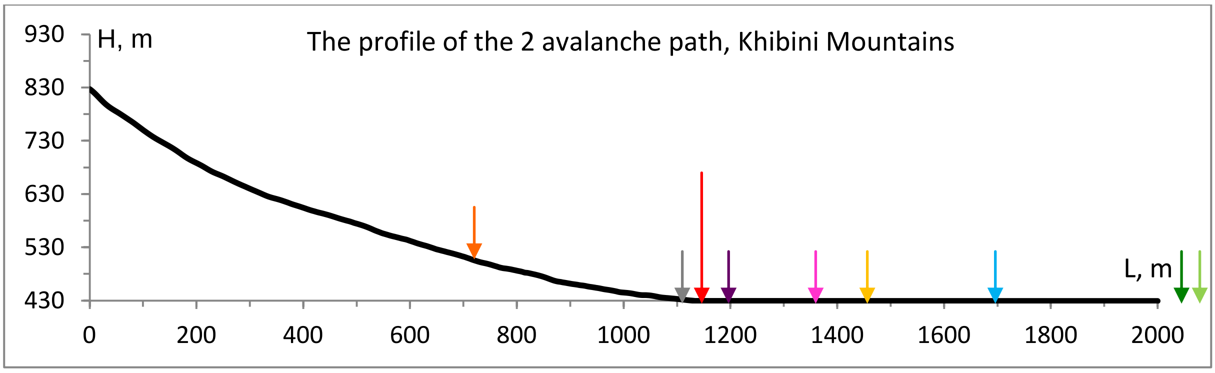


Figure 2. An example of the calculated «maximum» avalanche runout distance using different statistical runout models. The color of the arrows corresponds with tables 1 and 2. Red arrow - actual «maximum» avalanche runout since 1960th.

The distribution of the calculated runout distances using different statistical methods and the «maximum» actual value (since 1960th) on the profile is more or less the same in the avalanche paths with similar topographic parameters. Concerning extreme avalanches we can assume that the runout distance as well as its return period is determined by the topography of the avalanche path and the initial conditions in the release zone. Using the avalanche database (Vikulina, 2009), probability curves for the runout distance (expressed in terms of 1/f) were constructed and extrapolated with analytic curves to the low probability values. It allowed us for each considered avalanche path to calculate the probability (Table 2) and them to assume the return period of the calculated runout distances for different statistical models.

In order to find out a way to apply our results beyond the considered test sites the cluster analysis of avalanche paths was performed. Topographic parameters such as the area of the potential release zone, mean slope angle and the relative elevation of the avalanche paths were classified. More than 300 avalanche paths were divided into 4 classes. We assumed that the runout probability curves within the same cluster are similar. Due to this assumption we can roughly estimate the runout distances and its return period using different statistical models within each cluster.

Table 2. The probability (P, %) of an avalanche reaching the calculated runout distance using different statistical models in the avalanche path №2, Khibini Mountains.

Moskalev, Efimov, 1972	Zalihanov, Runich, 1978	Zolotarev, 1981	Severskiy, 1978 (1)	Severskiy, 1978 (2)	Ebralidze, 1990	Akkuratov, 1961	Blagoveshensky, 1973
0,15	0,7	1,25	<0,1	<0,1	0,7	<0,1	20

3 RAMMS FOR AVALANCHE HAZARD ASSESSMENT IN RUSSIA

The avalanche dynamics program RAMMS, developed in Switzerland by the SLF (Christen et al., 2010) using the VS model was verified by the data from the Khibini Mountains and the Caucasus. The 5 m resolution input DEM was used in both regions. The calculation (output) resolution was specified as 5 m and 10 m in some cases. Release zones and fracture snow heights were specified from the digital large-scale avalanche database (Figure 1). We used the possibility to prescribe the friction parameters manually as well as the option to use the automatic procedure given by the program. The values for the parameters chosen are based on terrain features such as open slope/flat terrain/channeled/gully or forested/non-forested (Gruber and Bartelt, 2007) according to the friction parameter table given for Switzerland. The friction parameters could be variable when they are modified by the automatic procedure or could be chosen constant over the avalanche path. In this paper snow entrainment as well as temperature effects are not considered.

4.1. Khibini Mountains

We applied RAMMS to simulate more than 50 well-documented avalanche events recorded in 7 avalanche test sites in the Khibini Mountains with volume from 2 000 up to 120 000 m^3.

We started to simulate all avalanche events from the digital large-scale avalanche database using the VS model with reference to the friction parameter table given for Switzerland in order to back-calculate them. According to this table, friction parameters μ and ζ depend on the altitude (m.a.s.l.) and are usually specified corresponding to the altitude limits as, above 1500/1000 – below 1500/1000 m.a.s.l. The highest point of the Khibini Mountains is 1208 m. All considered avalanche paths are located on the altitude below 1000 m. The comparative analysis of regional characteristics of the Khibini Mountains and the Swiss Alps showed us that the mean annual temperature of the coldest month at an altitude of the most common avalanche release zone is almost similar in both regions. While the altitude of the Khibini Mountains is relatively low, the release zones are steep enough (35-40^0 on average). Slab avalanches are dominating in both regions. Due to these facts, indicating that avalanches hardly depend directly on the altitude, but rather on climatic conditions, we used for the Khibini Mountains (polar region) the μ and ζ values “above 1500 m.a.s.l" given by the table recommended for Switzerland. As a result we were able to back-calculate shapes of most observed avalanches (mainly medium avalanches with volumes 25 - 60'000 m^3). Concerning maximum avalanche speeds they correspond in general to the values measured in this region. According to the results obtained by the simulations we argue that our assumption works satisfactory and could be recommended (until we know better) for the future RAMMS application by practitioners for the avalanche hazard assessment in the Khibini Mountains.

4.2. Caucasus

Extreme rare catastrophic avalanches are a threat to villages, roads as well as recreation areas in the Mt. Elbrus region. The goal of our investigation was to test the capabilities of RAMMS to model the flowing behavior of such avalanches, as well as to compare the observed runout distances. The detailed description of the largest observed extreme avalanche (volume 2 100 000 m^3) recorded in 1973 by Zolotarev (1981) was used in this study. This avalanche released on the north face slope of the Mt. Cheget (upper part of the Baksan valley). The simultaneous release covered an area of almost 70 hectares. Two avalanche release zones are acting on this area as usual. The return period of the avalanche is 300 years according to the vegetation analysis. As input we specified the observed release zone. The specified fracture height corresponded to the mean observed value of 3 m. The forest was considered during the simulation and specified according to the remote sensing data. We simulated this avalanche with the VS model with a 300 year return period using variable friction parameters obtained from the automatic procedure implemented into RAMMS (values recommended for Switzerland). As a result RAMMS almost reproduced the observed starting and transit zone behavior and reconstructed the outline (Figures 3 and 4) of the observed avalanche in the runout zone.

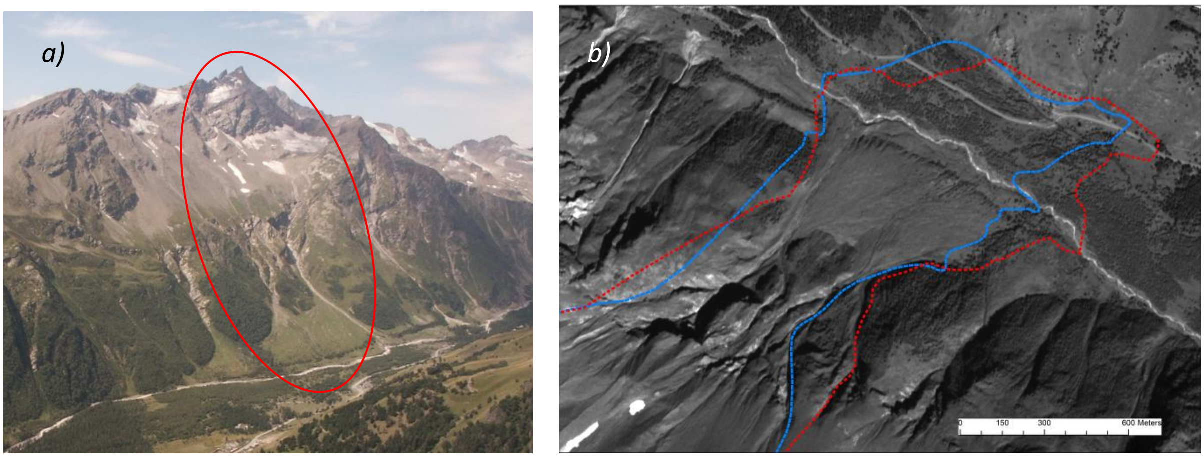


Figure 3. *a)* Area of interest (photo courtesy of Yuri Seliverstov); *b)* The outlines of the observed (blue line) and the RAMMS simulated (red line) avalanches.

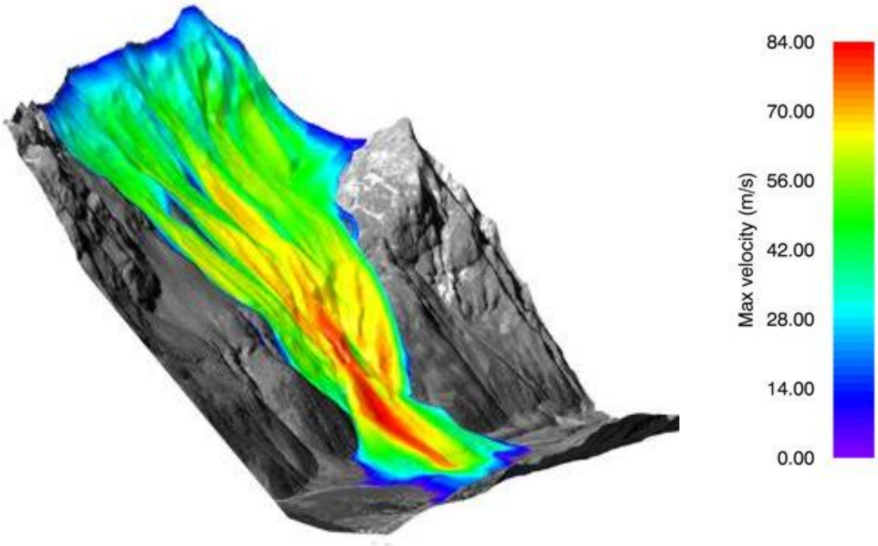


Figure 4. Avalanche RAMMS simulation results (3D visualization) superposed on a satellite image.

According to the obtained result (taking into the account the tremendous volume of an avalanche) we argue that RAMMS could be used for simulation of rare extreme avalanches in the Mt. Elbrus region using the values of the friction parameters recommended for Switzerland.

5 CONCLUSION

Statistical runout models could give only a rough idea about the runout distance and its return period. They cannot show the avalanche flow behavior and therefore are not relevant in avalanche terrain that consists of several flow channels as well as in the narrow valleys. The obtained variety of the results by different statistical runout models in the Khibini Mountains casts doubt on the effectiveness of their application for the avalanche hazard assessment in Russia.

The avalanche dynamics program RAMMS was tested in the Khibini Mountains and in the Caucasus, Russia for the first time. According to the obtained results in both regions we state that RAMMS should be implemented into Russian avalanche hazard assessment practice as a powerful tool that can resolve a lot of problems. The friction parameters (μ and ζ values) may be taken from the upper altitude limit (above 1500 m.a.s.l.) of the table recommended for Switzerland (implemented into RAMMS) for simulations in the Khibini Mountains. In such a way a high level of correspondence of observed and simulated avalanches was found. RAMMS could be used for simulation of rare extreme avalanche events in the Mt. Elbrus region using friction parameters values recommended for Switzerland. We hope that our results can be helpful for the future development of avalanche hazard zoning it in Russia.

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