Destroying Avalanche-Like Processes in the Khibiny Mountains: Damage Mitigation

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Abstract

The main dangerous avalanche-like processes in the Khibiny Mountains are: snow avalanches, slushflows, rock avalanches and mudflows. All these processes are quite different to be described identically, but similar enough to use common approaches for certain purposes. Statistics for avalanche parameters and characteristics of avalanche regime obtained with observations since 1936 are presented. Such measures of avalanche danger prevention as avalanche forecasting, artificial avalanche release, risk mapping, protective constructions and some other are described. Special attention is devoted to artificially triggered avalanches (by seismicity and air shock waves caused by blasting). Slushflows are more rare phenomenon than snow avalanches, but no less destructive. They have been studied in the Khibiny Mountains more than fifty years. A short description of the Khibinian slushflows and the methods of their forecasting are presented. Rock avalanche problems are resulted from open pit mining. Two types of the technogenic rock avalanches are considered. In the first case the rock avalanches are formed of rocks deposited on the mountain slopes and in the second one they are formed of rocks that come to be on an open pit flank as a result of technological blasting. Since slopes are mostly covered by snow and spoil heaps include significant amount of snow, a glacial factor has a great importance in their stability and rock avalanche dynamics. It is resulted evidently in very low effective friction coefficients and therefore big run out distances. However, failures of the spoil heap stability are not connected with snow melting season. Rate of spoil heap vertical deformations and threshold rate of the deformation are used for spoil heap stability control now. Description and statistics of the most interesting rock avalanches as well as methods for the avalanche danger prevention are presented. Mudflows are rare and less dangerous phenomenon among mentioned above. Short description of the Khibinian mudflows is also presented. The work has been supported by Russian Foundation for Basic Research, grants: 05-05-64037-a, 05-05-64368-a, 04-05-65057-a.

Keywords: natural and technogenic snow and rock avalanches, slushflows, mudflows, monitoring and forecasting, disaster mitigation

Introduction

The Khibiny Mountains located in the middle of the Kola Peninsula beyond the Polar Circle in the European part of Russia are a small flat topped massif with area about 1300 km^2. Mountaintops have elevation about 400–700 m above valley's bottom. Upper parts of the slopes are steep enough, up to 40°–45° and devoid of trees. The "Apatit" mining company has began its activity in this area in 1929. Snow avalanche problems arose ever since. In December, 1935 89 people were lost and tens wounded in an avalanche accident. Center of Avalanche Safety (CAS) was founded in Kirovsk in 1936 to study and prevent avalanche damage. Nevertheless about 70 people have been lost in avalanche accidents in the Khibiny Mountains since then. Most of them were lost beyond the bounds of CAS responsibility. There were also heavy material losses.

In the fifties, people in this area came across a new destructive phenomenon subsequently called slushflow. The slushflows are more rare phenomenon than snow avalanches but no less destructive.

Rock avalanches have a technogenic origin connected with intensive mining in this area and shifting great rock masses onto the slopes. Rock avalanches are the most large-scale and destructive avalanche-like processes in the Khibiny Mountains. Rock avalanches caused no heavy looses due to preventive measures and as they occur in inhabitant area.

Mudflow is less dangerous and very rare event among considering phenomena.

The paper has a goal to acquaint reader with main hazardous avalanche-like processes in the Khibiny Mountains and their peculiarities as well as approaches to mitigate damage caused by them.

pp. 255–266

Snow avalanches

Characteristics and regime

Usually snow avalanches are released from November to May, but sometimes the releases are observed in June and October. Most of avalanches are caused by overloading of snow pack due to snow drift deposition in avalanche starting zones. Weakening of underlying snow layers due to re-crystallization also causes big avalanches. There is a specific avalanche type — triggered by explosions avalanches. Dry and wet snow slab avalanches are the most frequent and dangerous. Field measurements showed that volume of avalanche deposition may exceed $0.5*10^6$ m^3, avalanche depositions average amount of registered avalanches is $2, 7*10^3$ m^3, avalanche speeds up to 51 m/s and impact pressure more than 10^6 Pa. CAS files contain data on more than 6600 avalanches. Study of distribution of slab avalanche geometric characteristics at starting zones showed that some of them can be described with power low (Chernouss and Kozelov, 2004). The same data was obtained for other mountain areas (Birkeland and Landry, 2002, Faillettaz et al., 2002, Rosenthal and Elder, 2002). It is a proof of avalanche formation accidental occurrence. Therefore, the only way out for avalanche prediction is to do that in probabilistic manner.

Technogenic avalanches

Technological explosions at mines and mortar shooting for preventive avalanche release are the most important triggers for avalanches in the Khibiny Mountains. There are at least three explosion factors which influence on snow stability, namely: i) ground shaking, ii) air shock waves impacting on snow surface and iii) direct snow "push" caused by the explosion in snow. It is clear that (Mokrov et al., 2000) significant statistical dependence between technological explosions in the mines and avalanche releases exists. Mortar shooting (Fig. 1) has been used effectively for preventive avalanche release since 1938; quantitative theory of explosion influence on snow stability as well as rational methods of explosives using is still not developed. There are some proves that trains motion can cause avalanche release (Rzhevsky and Matvienko, 1980), but it requires more careful study.

Another type of technogenic avalanches is that when avalanches release on artificially made slopes, such as dam slopes and open pit flanks. Avalanche releases were observed on slopes of avalanche protective dams.

Damage mitigation

A few approaches are used to mitigate damage caused by snow avalanches. Avalanche forecasting combined with safety plans is the main preventive measure. Artificial avalanche release is also effective for damage mitigation and has been widely used in the Khibiny Mountains to decrease avalanche danger in a short space of time. Many different protective constructions have been built in places for with extremely reliable protection of the objects.

Fig. 1. An avalanche caused by mortar shooting drops to an open pit.

Forecasting

Diagnostic and forecast models are considered as a set of formal rules for interpretation of input data and obtaining quantitative or qualitative results on avalanche occurrence possibility. In practice these models which forecast an exact time and exact place of avalanche occurrence have not been used in CAS. Usually they just allow to predict the avalanche danger period. Therefore, it is a real-time avalanche diagnostics rather than a forecast; some models are just rules for classification of the situations which say nothing on avalanche occurrence before or after the moment of diagnostics. Categorical conclusions as "avalanche situation" and "non-avalanche situation" are made on the basis of calculated and threshold probabilities. Some models can be applied to all genetic types of avalanches, other - to special ones only. Brief description of the models is given below.

Zelenoy's (1937) method — an empirical rule developed for a small area of 550 km^2 with about 50 avalanche sites. It was considered that at least one avalanche release could occur during the days when the wind speed at the valley weather station was more than 10 m s^{-1}. The wind speed 10 m s^{-1} is very close to the threshold wind when snowdrift starts. The rule was true for avalanche situations, but failed in recognising of non-avalanche situations.

Akkuratov's (1956) model — an empirical rule, which uses snowdrift intensity measurements at the top of the mountain instead of indirect snowdrift characteristics. The model is used for so called snowstorm avalanches, which are formed of fresh snow and release during the snowstorm. Avalanche period starts when total amount of drifted snow with intensity 0.25 kg m^{-2}s^{-1} in 2 cm near surface layer is overcoming 1000 kg/m. This rule is applied to the same area as Zelenoy's method. Quality of avalanche forecasts with this rule significantly higher than with Zelenoy's method (Chernouss, 2000).

Linear discriminant analysis — discriminate situations with a linear function in multivariate space of diagnostic parameters. There have been used two types of a linear discrimination analysis. First one (Chernouss, 1975) was developed for avalanche situation recognition in a group of four avalanche sites located very close one to another and having almost the same starting zone inclination and aspect. The model was applied for snowstorm avalanches. Nine weather and snowdrift characteristics, which define snowfall from the beginning to the moment of diagnostics, were taken as the diagnostic parameters. In the second scheme (Chernouss et al., 1998; Chernouss et al., 1999) of the analysis snowfalls were classified on "avalanche" and "non-avalanche". A snowfall is considered as "avalanche" one when at least one avalanche release is observed in the area (the model is applied to the same area as Zelenoy's and Akkuratov's models). The discrimination functions where obtained for each sixth hour since snowfall beginning. This model's advantage is an opportunity to use different evaluations of mathematical expectations and variances of the parameters at different stages of the classification. Quality of the classification increases with time since snowfall begins, that is averaged trajectories "avalanche" and "non-avalanche" snowfalls in a space of the diagnostic parameters diverge more and more with time. CAS is using this method now. At different stages of diagnostics a percentage of correctly discriminated "avalanche" and "non-avalanche" situations varies from 87% and 36% to 91% and 93% respectively.

Bayes' formula — the model was worked out by Zuzin (1989) and has been used in CAS since 1978. The model is applicable for all genetic types of avalanches without any differentiation. A situation is considered as avalanche one when at least one avalanche release is observed in the area for which all above-mentioned models have been used. Two groups of empirical probable densities were obtained for days with avalanches occurrence and days with no avalanches occurrence on the basis of meteorological measurements and avalanche release records with such parameters as: snow height, daily precipitation, average daily wind speed and average daily temperature. Bayes' formula uses these distributions to recalculate a priori probability of avalanche situation, taking into account the data on current situation, described with the same parameters. In practice, 24 h gliding averages are used as input parameters for classification of gliding one-day periods on "avalanche" and "non-avalanche". The method is used in CAS activity, considered to be quite sufficient and gives good representation of avalanche danger dynamics.

Statistical simulation — the main idea of this method is to generate input data for deterministic models of snow cover mechanical stability on mountain slopes (Chernouss, 1994). The data is generated in accordance with statistical lows of the snow cover parameters spatial distributions. The simulation was used for two dimensional slope of arbitrary configuration. Parameters of the snow cover were represented by stochastic functions and snow stability for real slopes was calculated for separate profiles. Evaluations of snow height, density and shear strength mathematical expectations, their variances and autocorrelation functions were used as input parameters for the model. The results of the classification were the probabilities of snow release for different segments of the profile and probability of avalanche release. Subsequently the method was improved and applied for 3D-slopes (Chernouss and Fedorenko, 1998). This model was not examined reliably due to lack of data. Twenty situations (8 avalanche and 12 non-avalanche ones) were discriminated on avalanche and non-avalanche (by highest probability) with only one mistake as non-avalanche situation was recognised as

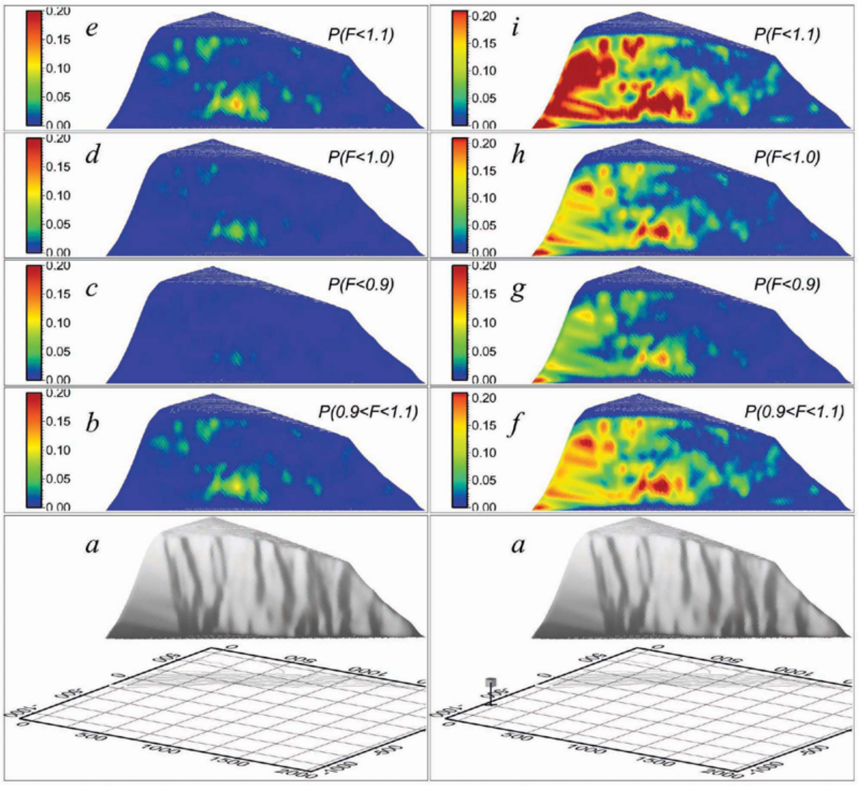

Fig. 2. The static probabilistic analysis results. A left-hand panel represents the stability factor distribution with no seismic load while a right-hand panel demonstrates risk changes induced by the explosion dated by 04/06/2001. F is the stability factor. F > 1 for a stable snow pack and F < 1– for an unstable snow pack (Chernouss et al., 2002).

avalanche one.

Synoptic model — is used for snowstorm avalanches forecasting. This model (Izhboldina, 1975) relates avalanche releases with previous synoptic situations (24 hours before). Each situation is described as a set of parameters to evaluate avalanche releases probability. Later this method was formalized with discrimination analysis. Due to low spatial resolution of the forecasts this method wasn't used as a formal procedure; now synoptic information is taken into account only subjectively.

Most of the mentioned models, avalanche dynamics models inclusive are used in a computer-assisted work for avalanche forecaster — LAVINA-1 that is exploited in the Centre for Avalanche Safety of "Apatit" JSC more than ten years. Avalanche dynamics is simulated by a simple deterministic method approved by Russian government for use by construction industry where the avalanche is considered as a material point moving with effective friction. At this stage one-dimensional two-parameter block model is also included in the software.

Main advantage of the software is that it allows to integrate all models into a single entity to make spatial and temporal avalanche risk evaluations automatically almost in real time regime (Chernouss and Fedorenko, 2001).

Forecasting of seismicity-induced avalanches — Two approaches of evaluation seismic effects on snow stability and avalanche release have been worked out (Chernouss et al., 2000; Fedorenko et al., 2000). A balance of gravitational, friction, cohesion and inertia forces (caused by underlying surface shaking) effecting on snow is considered using static approach. Seismic effect in this case is described with peak ground acceleration. In dynamical approach (Newmark, 1965) temporal changing of seismic acceleration is taken into account. Both approaches were realized in deterministic and stochastic manner (Fig. 2). They are very useful tools of an avalanche forecasting since it allows to represent seismic effect on snow stability spatially, at least relatively.

Fig. 3. Catching dams

Fig. 4. A protective concrete fence.

Preventive release

Preventive avalanche release has been used in the Khibiny Mountains since the early thirties. The most frequent method to trigger avalanches is mortar shooting. Since thirties, the mortars of 82, 120 and 160 mm caliber were used. 160 mm mortar is the most effective since it has up to 9 kg of explosives in the shell. In the eighties almost a half of avalanches near Kirovsk were released by explosions. Average volume of snow released by shell during all these years was 320 m^3. In some winters expenditure of shells exceeded seven hundred. In the last years shell expenditure reduced due to better avalanche forecasting and construction of avalanche protection.

Protective constructions

Many types of protective constructions have been built in the Khibiny Mountains. Different types of dams (Fig. 3), walls and fences (Fig. 4), splitters, mounds, etc. were constructed in avalanche runout zones. Avalanche protective dams are the most common and technological constructions in the considered area, since enormous mining company operates here. It is very convenient to store spoiled rocks as avalanche protective dams. Length of the longest dam protecting part of the city is about 900 m and height of the highest one is more than 30 m.

An experience of exploitation of snow fence on the border of the plateau and avalanche starting zone to reduce snow deposition and supporting construction to prevent avalanche release has shown that they are not effective due to intensive snow drift. In one case a tunnel in the mountain was built to make railway connection more reliable.

Slushflows

Regular observations of slushflows in the Khibiny Mountains have been carried out by the Centre of Avalanche Safety of “Apatit” JSC since fifties. The observations cover about twenty sites where slushflows

Fig. 5. The front of slushflow deposition.

Fig. 6. A concrete structure destroyed by a slushflow.

occur. All sites are within a relatively small area, a radius of less than 15 km. The heights of the slushflow starting zones vary from 300 m a.s.l. to 800 m a.s.l.

Characteristics and regime

All the registered slushflows have occurred during spring break-up between 28th of April and 10th of June. Volume of snow involved in slushflows varied from a few cubic meters to tens of thousand cubic meters. (Fig. 5). Direct measurements of slushflow impact forces haven't been done but there are some proves that they can exceed avalanche ones. Concrete constructions that many times suffered avalanches but were destroyed by slushflow are shown in Fig. 6.

Forecasting

The linear discriminating analysis and direct application of Bayes' rule were chosen for classification of the situations onto "slushflow" and "non-slushflow" (Chernouss et al., 1998). Situations were described with daily water income — a parameter calculated on a base of standard meteorological observations (Harstveit, 1984) and snow height. To avoid data heterogeneity connected with elevation differences of slushflow starting points and meteorological stations all data of meteorological stations were interpolated to different levels from 300m.a.s.l. to 800m.a.s.l. with a step equal 100m.

Classification matrix for discrimination of "slushflow" and "non-slushflow" days in the Khibiny Mountains showed: 85.4% of all days were successfully classified; 78.8% of "slushflow days" were successfully classified; 85.5% of "non-slushflow days" were successfully classified. Classification matrix for mountains of Norway gave respectively: 87.3%; 76.0%; 88.4%. Quality of the diagnostics is enough high for first numerical models.

Fig. 7. A slushflow protective dam. Cleared inlets of the drainage are easily seen. Some of these are marked with poles.

Protective constructions

Only two slushflow protective dams were built in the Khibiny Mountains. There were a few cases of slushflow interaction with dams and they worked well. Since the dams have drainage it has to be cleaned before slushflow period starts (Fig. 7).

Rock avalanches

There are a few types of technogenic rock slide formation in the Khibiny Mountains. The biggest and most frequent slides are formed of spoil heaps. Waste rocks from the located on the mountain plateau the "Central" open pit mine are stored in heaps on the mountain slopes. Heights of the slopes above the valley bottom usually exceed 200–400 m and rarely 500–600 m. From time to time these heaps are released as rock avalanches. The open pits of the "Apatit" mining company, that are located on the mountain plateau and in the valleys, have depths 300–500 m and enough long adjacent slopes that can be an underlying surface for rock slides under certain conditions. It can be throwing of rocks by explosion on an open pit flank. There are also other types of the technogenic slides in the Khibiny Mountains, but only two mentioned above are considered here. These slides look like rock avalanches and this term will be used for them in the paper. The schemes of such avalanche formation are presented in Fig. 8. First problems with rock avalanches arose in the sixties. Many of the approaches that have been used for snow avalanches are applicable to rock ones.

Characteristics and regime

First technogenic rock avalanche formed of spoil heap was registered in 1967 as a result of the "Central" mine activity. More than twenty avalanches have been registered in this area since that time. Average volume of their depositions was about 2.3×10^6 m^3. For the biggest one it was 6.0×10^6 m^3. Only big avalanches with volume more than 0.5×10^6 m^3 were registered by mine-surveying service. The avalanches of lesser volume were observed more frequently in lower parts of the heaps. The avalanche that had the biggest runout distance, about 3.7 km, was released 13.06.73. The avalanches consist of rock pieces that have wide range of size, from less than 1 cm to 1.5 m (the most typical size — 0.1–0.3 m). The avalanches formed of rocks that occur in an open pit side as a result of technological explosion are smaller and very rare. The biggest one occurred 05.01.05 as a result of miscalculation of the explosion and had volume of deposition about 7×10^4 m^3 and runout distance about 145 m.

Since the avalanches of the spoil heap were unexpected due to open pit design, any measurements of their dynamics were not taken. All the avalanches occurred in the unpopulated valleys and their dynamics doesn't attract any attention. But for the big avalanche released in 1973 (Fig. 9) which had an extraordinary long runout distance, some measurements and descriptions have been done. The avalanche of volume 4×10^6 m^3 had a horizontal projection of the runout distance L = 3.7 km and starting point elevation above front edge of the avalanche deposition H = 480 m. Height of the fracture line was about 800 m a.s.l., length — about 1 km, maximal thickness of crown surface — 20–25 m (Rzhevsky and Samoylov, 1974). Unusually low ratio H/L = 0.13 is an evidence of very low effective resistance coefficient. Snow avalanches have more high coefficients

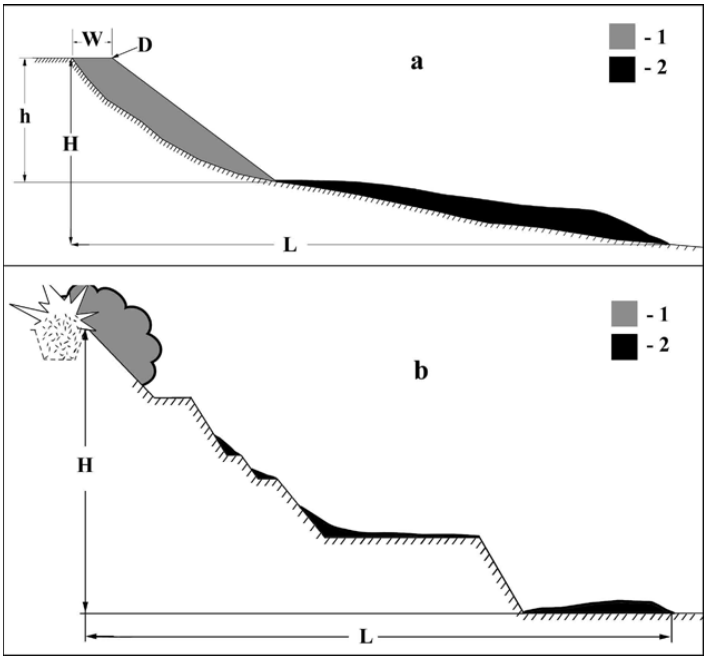

Fig. 8. The technogenic rock avalanche formation: a) an avalanche formed of a spoil heap deposited on the slope; b) an avalanche formed of rock that come to be on an open pit board as a result of technological blasting. 1 — the avalanche initial position; 2 — the avalanche deposition; h — the deposition height, H — the elevation of the highest point of avalanche release above the front end of avalanche deposition; L — the avalanche path horizontal projection length; D — the heap deformation measuring point

Fig. 9. The view of the rock avalanche fallen down on 13.06.1973.

of resistance. Such low coefficients are characteristic for slushflows with high content of water. In case with the rock avalanche, water content was very low, mainly, water formed of snow and ice buried in the spoil heap. Head part of the avalanche consisted of enough dense slush, but there were no water streams out of it. Evidently the friction coefficient changes significantly during avalanche motion because properties of the avalanche material also changed due to snow and ice melting, disintegration of frozen conglomerates, capture of soil at the avalanche front and so on. As speed in the tail part of the avalanche is relatively low and inertial effects can be neglected, it is possible to estimate dry friction coefficient $\mu = \mathrm{tg}\varphi$ with slope angle φ at the tail of the stopped avalanche. For the considered avalanche it was 0.18. Taking this value as a constant for the whole path, the run out distance will be considerably modest even with no turbulent resistance taking into account. Grigoryan and Ostroumov (1975) assumed that dry friction is dependable on shear stress value of the underlying surface $\tau = \mu \times \rho \times \mathbf{h} \times \mathbf{a}_{\mathrm{y}}$, where: ρ — avalanche density; $\mathbf{h}$ — avalanche thickness; $\mathbf{a}_{\mathrm{y}}$ - projection of particle acceleration on perpendicular to the slope. It is assumed that τ can increase only up to

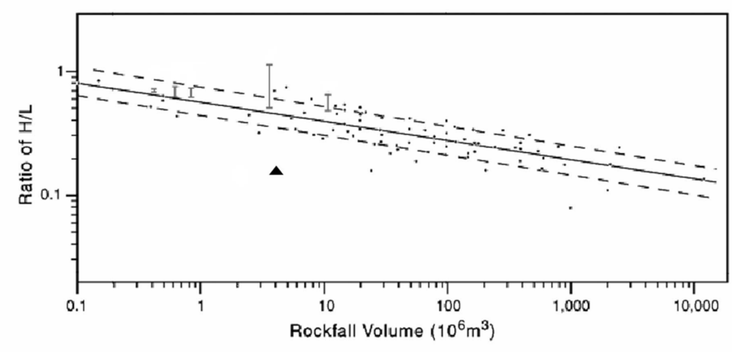

Fig. 10. The plot of volume versus the H (height)- to- L (length) ratio of worldwide rock avalanches (modified from Li, 1983). The bar indicates the range of uncertainty for measurement of the H/L ratio for avalanches in the Yosemite valley (Wieczorek et al., 1999). The triangle corresponds to the H/L ratio for the Khibiny rock avalanche of 13.06.1973.

τ_* — critical stress when the weakest of rubbed materials is collapsed. Test calculations with one-dimensional hydraulic model (Grigoryan and Ostroumov, 1975) show that required run out distance can be obtained with $\mu = 0.18$, $\mathbf{k} = 0.15$ and $\tau_* = 2.6 \times 10^4$ Pa, where $\mathbf{k}$ is a coefficient of turbulent resistance. Obtained for this avalanche value of τ_* corresponds to normal of underlying surface pressure $1,5 \times 10^5$ Pa and critical $\mathbf{h}_*$ about 7 m. Besides of coincided calculated and real run out distances there was a coincidence in distribution of avalanche deposition depths. Maximal calculated avalanche speed was about 20 m/s. The model can be improved but it requires data on moving avalanche. For practical purposes simple graphical method is used. Run out distance determines as a length of horizontal projection of line between probable starting point and point of intersection of the slope profile and straight line drown from the starting point under angle (to the horizon. This method gives too high run out distances for other avalanches.

Dynamics of avalanches caused by throwing of rocks on an open pit flank during technological explosions is simpler. Most of the dry friction coefficients correspond to obtained data on rock falls. In some cases they can be a little bit less due to snow covering open pit flanks in wintertime. The ratio H/L for the biggest avalanche of this type occurred 05.01.2005 and it was 0.5. It corresponds to lowest limit for registered rock falls (Fig. 10). For this type of the rock avalanches, besides low friction coefficients, H/L ratio can be less than for natural ones because rocks can have some initial speed at starting point caused by explosion and their further fall on an open pit flank.

Stability assessment and monitoring

The "Central" mine has been exploited since 1962. The only places to store spoil were the slopes adjacent to plateau. The slopes are enough high (up to 600 m) and steep (up to 50°). According to the original open pit design all spoil was deposited in one big heap of 4×10^8 m^3 and be stable. The heap started to change form soon after its exploitation began. Measurements of its deformation had begun in 1964.

The rock avalanche release occurred in 1967. Firstly it was thought that thin layer of clay at the base of the heap could be the only reason for its release. Since the sliding surface of the first rock avalanche (18.09.67) was inside of the heap body, it was decided that the reason of the release was ice thawing and snow buried in the spoil heap. It was thought that heaps of north aspect would be stable. But in 1973 rock avalanche released from the slope of the north aspect.

Analysis of avalanche releases dates shows that they are not dependable on time of the year. Cold snow increases the strength of material of what the heap body consists of. Increasing snow percentage in spoil from 0% to 15% at stable temperature below $-2°$ C results in increasing shear strength on 35–50%, but increasing temperature from $-2°$ C to $-0.5°$ C with snow percentage 10% in spoil decrease it on 30–45%. Absolute values of shear strength varied in wide range from 1.5×10^4 Pa to 5×10^4 Pa (Krasnoselsky et al. 1975). The heaps that are exploited only in wintertime have bigger volumes before avalanche release than ones exploited all year around. Season temperature changes penetrate into a heap body only in a few meters and thus permafrost occupies the most of the heaps. Some heat can come to the heaps with rain in summer time, but in common case it is insignificant for snow and ice melting. Of course this effect can appear in the heaps with special distributions of rocks and snow inside them.

As observations show that heaps higher than 210 m were unstable and lower than 150 m were stable. It was found that heap stability depends on its volume and intensity of loading. Amount of spoil coming in a

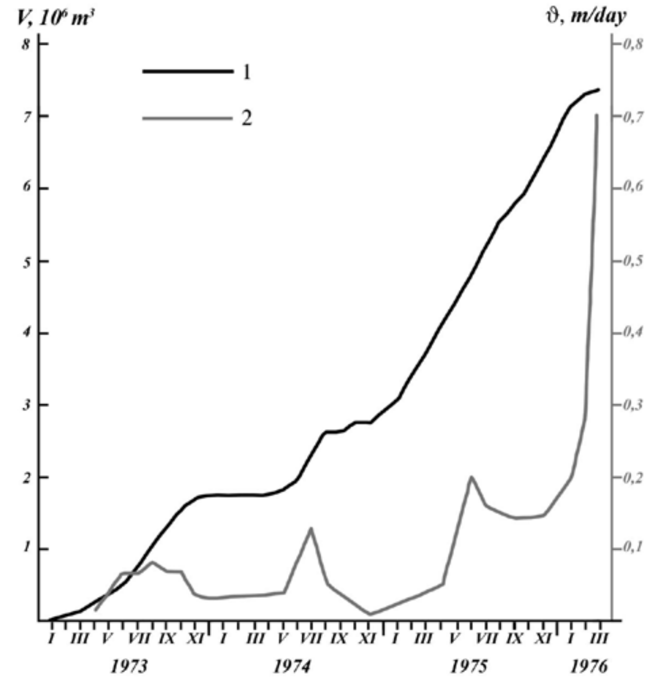

Fig. 11. Temporal changing in volume and monthly average vertical deformation rate for Spoil Heap No 17. The avalanche release occurred on 13.03.1976.

heap can exceed 6×10^6 m^3 per year. During a day amount of spoil coming in a heap can exceed 2×10^4 m^3.

The heap deformations varied within the wide range of values — from one centimetre to more than ten meters a day. In the initial stage of the heap formation densification deformations prevail, then sliding ones. An example of temporal changing of spoil heap volume and vertical deformation rate is presented in Fig. 11. Vertical deformation rate at the point D (Fig. 8a) is the most informative parameter for instability diagnostics. Measurements of these heap deformations, their rates and observations avalanche releases gave opportunity to divide stable and unstable situations and find out an empirical criterion of heap stability. Vertical rate of the deformation — $\vartheta = 0.5$ m/day was chosen as the criterion. In practice it works enough well. Usually when heap is not big after loading stop, the deformation rate decreases; sometimes it is possible to unload trucks again. When the heap big enough, it is possible that deformation will progress in spite of stopping truck's unloading. According to existing instruction, measurements of vertical deformations have to be done once a week if the deformation rates are less than 0.1 m/day; two times a week if rates are in interval 0.1–0,25 m/day and once a day if rate higher than 0,25 m/day. The heap is closed to truck unloading when rate exceeds 0.5 m/day. Exploitation of the heap begins when the deformation rate drops below 0.2 m/day. Average number of days from date when $\vartheta \geq 0.5$ m/day to avalanche release is 19.

Analysis of data on technological explosions in mines in the Khibiny Mountains and snow avalanche releases showed statistically significant correlation between these phenomena (Mokrov et al., 2000).

Measurements of seismic accelerations caused by explosions on adjacent slopes show that they can make tens of percent of gravity acceleration (Chernouss et al., 2004). To carry out experimental and theoretical studies of seismic effects on the spoil heap stability are in perspectives.

Mudflows

Mudflows in the Khibiny Mountains are the rarest avalanche-like process (see Fig. 12). Genetically they are connected with heavy rainfalls. The mudflows occur on slopes of inclination 25°–35° covered by moraine depositions of 0.3–1.0 m thickness. Since they occur in the inhabitant areas and due to their rarity and small scale there was no significant damage caused by them.

Fig. 12. A mudflow typical for the Khibiny mountains.

Concluding remarks

Valuable experience of damage mitigation of the avalanche-like processes in the Khibiny Mountains has been obtained during 70 years of study. There were developed quite effective safety plans, exact maps of potential avalanche danger, reliable protective constructions and some methods of preventive avalanche release. At the same time quantitative description of avalanche formation and motion with high spatial and temporal resolution was not sufficient. Lack of adequate models, poor initial information (at best, measurements are done in some points), spatial variability of media properties and internal properties of the processes are the main reasons of such situation. In this connection it seems that probabilistic descriptions of these processes are more adequate rather than deterministic ones. Integrated stochastic models for avalanche damage and risk evaluation (stability – dynamics – interaction with object – damage) are the most perspective (Chernouss and Fedorenko, 2001). Observations in the Khibiny Mountains have shown that industrial activity can significantly change avalanche regime and cause appearance of new phenomena. Technogenic effects on the avalanche-like processes have to be taken into account in taking measures for damage mitigation.

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