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DYNAMIC AVALANCHE MODELING INCLUDING SEISMIC LOADING IN THE KHIBINY MOUNTAINS

Yuri Fedorenko[1,2], Pavel Chernouss[3], Evgueny Mokrov[3], Eystein Husebye[2] and Elena Beketova[4]

ABSTRACT

The Khibiny mountains in Kola, NW Russia is avalanche prone during many months in winter times. In the past tragic accidents have taken place so already in 1936 the Centre of Avalanche Safety was established in Kirovsk for monitoring avalanche occurrences and issue warnings about avalanche risks. From the observational data at hand we have been able to establish a correlation between avalanches and mining explosions which implies that seismic loading on the mountain slopes in Khibiny occasionally triggers avalanches. In this joint study of 4 science groupings we carry this work a step ahead through dynamic modeling of the stability of a snow slab on steep mountain slopes, also subjected to seismic loading, using the Newmark (1965) and Jibson (1993) approach. From this platform, an extensive Monte Carlo simulation of the derived probability density function for the stability factor F was undertaken and obtained stability and risk results are presented and discussed for various snow slab and loading scenarios. Stability varies with respect to snow density, thicknesses, friction forces etc but is significantly degraded due to seismic effects as modeled from in situ explosion recordings from the Nansen (NKK) station. Our Newmark modeling including time histories of successive explosions will degrade stability stepwise until an avalanche is released. This also explain why the correlation between explosion activity and observed avalanches are not so easy to establish. Albeit results obtained are not directly applicable presently to hazard warnings a better dynamic understanding of physical processes causing avalanches would better future forecasts.

KEYWORDS: avalanche, seismic loading, stability factor, mining explosions

INTRODUCTION

There are some evidences pertaining to the seismic influence on avalanche releases but this phenomenon is not well understood and conceptual models of it are absent. It is very difficult to get information about avalanches released by earthquakes due to their rarity in avalanche prone areas. The Khibiny Mountains in Arctic Northwest of Russia are strongly affected by artificial seismicity caused by explosions in underground mines and open pits of "Apatit" mining company. There are some big explosions, with amount of explosives ranging from tens to hundreds tonnes, at underground mines and open pits almost every week. Distances from the places of explosions to the controlled avalanche starting zones vary from some hundred meters to a few kilometers. An avalanche hazardous period

[1)] Institute of Northern Ecology Problems; Kola Science Centre RAS, 14 Fersman St., 184200 Apatity, Russia
[2)] Institute of Solid Earth Physics, University of Bergen, Allegaten 41, N-5007 Bergen, Norway (eystein@ifjf.uib.no)
[3)] Centre of Avalanche Safety, "Apatit" JSC, 33a, 50 Years of October, 184230 Kirovsk, Russia, (P.Chernous@apatit.com)
[4)] Institute of Geology, Karelian Science Centre RAS, Pushkiskaya 11, 185030 Petrozavodsk, Russia, (elena@krc.karelia.com)

lasts about 7-8 months in a year. Centre of Avalanche Safety (CAS) of "Apatit" mining company began regular snow, avalanche and meteorological observations in 1936, thus this place is favorable for studies of seismicity-induced avalanches. Such joint Russian - Norwegian studies were started by CAS, Institute of Northern Ecology Problems, Kola Science Centre of Russian Academy of Sciences and Institute Solid Earth Physics, University of Bergen in 1999. At the first stage data on explosion and avalanche release distributions over days of week were analyzed. It has been shown that avalanche releases clearly correlated with explosions. To quantify underlying seismic disturbancies the Nansen seismic station (Chernous et al., 1999) equipped with a high frequency Cossack Ranger data acquisition system (Fedorenko et al. 2000) was deployed on a mountain plateau, in a few kilometers from places of explosions. It records directly ground acceleration so no need to convert from displacement or ground velocity typical of most seismometer responses. Supplementary seismic data are available from the small Apatity seismic array (http://www.krsc.ru/) and some seismograph stations.

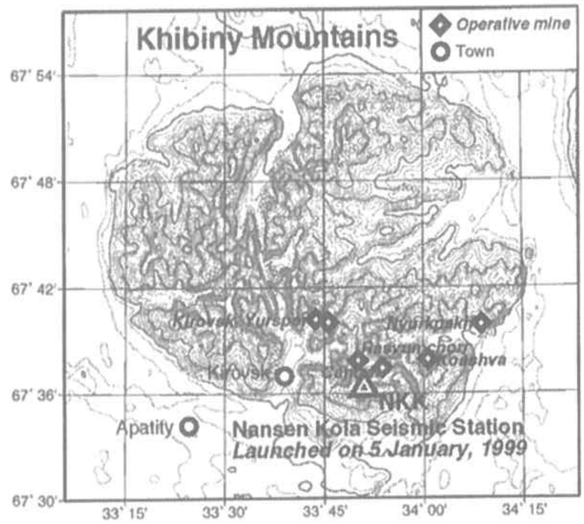

Fig. 1. Topographic map of the Khibiny Massif including locations of major towns, operative mines and 3-component Nansen station. NKK is close to several mines and besides offer an unique opportunity to study seismic influence on avalanche releases.

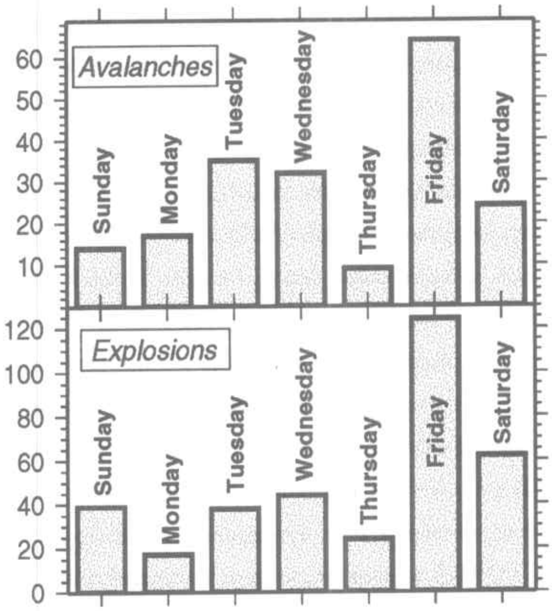

Fig. 2. Number of days with avalanches and mining explosions in the Central mine area. Notice the relative large number of Friday avalanches, which is clearly correlated with the large number of explosions on Fridays that is explosions trigger avalanche releases.

Main goals of the studies are: quantitative evaluation of interdependence between seismic events and avalanche releases; working out of a physically-based model for snow stability, taking into account the seismic effects and developing methods for seismicity-induced avalanches risk evaluation. The last point is especially important for the Khibiny Mountains where mining activity is continuing and number of skiers (tourists) is growing. The ultimate goal of the studies is risk mitigation through improved avalanche forecasting.

We start with the physical model of snow piles on steep mountain slopes and then dynamic conditions bearing on snow pile stability and release mechanisms - that is the birth of an avalanche. Our efforts are focused on a close-in explosion zone (from hundreds of meters to kilometers), trying to understand the role of seismisity in avalanche triggering caused by mine shots and establishing a correlation between felt earthquake and/or explosion intensity with maximal values of ground acceleration and its spectra.

STATISTICAL STUDIES

Approximately 225 avalanches in CAS avalanche cadastre were recognized as triggered by explosions at mines over the period 1959-1995. Decisions that the explosion is a main agent of the specific avalanche release or trigger mechanism are somewhat subjective and just the most probable. Statistic methods were used to prove interdependence between explosions and avalanche releases. Days with explosions and days with avalanche releases were analyzed for two regions with an open pit and underground mines (Mokrov et al., 2000). Explosions and avalanche releases day-of-week occurrences were taken into account. Distributions of explosions and avalanche releases as function of day of weak were constructed (Fig. 2). The chi-square test has shown that these two distributions are far from independence (hypothesis of independence $\mathbf{H}0$ can be rejected at 1% significance level). In addition, it is easy to see a shape similarity in the distributions of avalanche releases and explosions. Although the correlation between days-of-week distributions of explosions and avalanche releases is clearly being recognized and verified (Pearson's coefficient $R = 0.873$, hypothesis $\mathbf{H}0$: $R = 0$ rejected at 1% significance level), such statistical evidence can not be directly used for avalanche release forecasting and physical models must be involved. Contingency table analysis also shows that the correlation between days with avalanche releases and days with explosions is significant: hypothesis $\mathbf{H}0$ of independence rejected at 1% significance level by χ^2 test (Mokrov et. al, 2000). The degree of association between rows and columns in the table is 0.0427 by Kendall tau b statistics. Thus the correlation between days of mass explosions and avalanche releases is enough clear to be recognized but it is too weak to be used for avalanche prediction .

MODELING OF SNOW COVER SEISMICITY - INDUCED INSTABILITY

Seismo-induced avalanches occur when the sum of static and inertia forces acting on a snow layer element exceed the friction forces between element and the underlying body. The latter is also normally snow or ice stemming from snow falls in the autumn. For force modeling we need to specify the snow slab physically and common parameters here are:

- ρ is snow density; typical values abount 300 kg $\cdot$ m^{-3}
- h is snow thickness; typical values 0.5 - 2 m
- α is slope of mountain side; typical values 25 - 55 degrees
- $a_\tau^{\max}$ is maximal tangential acceleration of external load (usually seismo-induced)
- $a_n^{\max}$ same as $a_\tau^{\max}$ but normal-to-surface acceleration
- f is a friction coefficient between snow element and layer below; typical values 0.3 - 0.6
- c is shear strength; typical values 1000 - 3000 Nm^{-2}

In general, ρ, h, f and c vary over the snow slab $z\,(x, y)$ that is they are functions of position (x, y). In most cases these values are not exactly known and must be considered as random variables defined by their probability density functions p_ρ, p_h, p_f and p_c. Then a_τ and a_n are random time histories (random processes) which are usually normally distributed with zero mean and standard deviations σ_τ and σ_n. A condition for snow layer pseudo-static stability may be written as

$$\rho h(g \sin\alpha + a_\tau) < c + f\rho h(g\cos\alpha - a_n) \tag{1}$$

where g - gravity acceleration; $\vec{a}_\tau$ directed along the underlaying surface downwards while $\vec{a}_n$ - normally upwards. Real landslide (top soil, sediments) observations imply that violation of this condition is neccessary but not sufficient for an avalanche to occur. With this is meant that landslides do not start unless some internal slab deformation have taken place. The time span over which these deformations accumulate depends naturally both on strength and duration of the external loading. Such deformations are calculated using the approach originally developed by Newmark (1965) and more recently applied by Jibson (1993). The sliding mass is assumed to be a rigid block. Downslope deformations occur during the time periods when the induced peak ground acceleration within the slide mass a_{is} exceeds the critical acceleration a_c. In general, the smaller the ratio (below 1.0) of a_c to a_{is}, the larger are the number and duration of times when downslope movement occurs, and thus the greater is the total amount of downslope movement. The amount of downslope movement also depends on the duration or number of cycles of ground shaking. Since duration and number of cycles increase with explosion charge, deformation tends to increase with increasing shot size for given values of a_c and a_{is}.

We define F the stability factor as

$$F = \frac{c + f\rho h(g\cos\alpha - a_n^{\max})}{\rho h(g\sin\alpha + a_\tau^{\max})} \tag{2}$$

In the Khibiny we have measured $a_t^{\max}$and $a_n^{\max}$ through the NKK station (Fig. 1) which is situated about 3-4 km from avalanche starting zones (Chernouss et al., 1999). We obtained that as a first approximation $a_\tau^{\max} \approx a_n^{\max} = a^{\max}$. Taking into account the worst case when random variables ${a_\tau}^{\max}$ and $a_n^{\max}$ are closely correlated which means that random variable $a_\tau^{\max}(t)$ is in direct proportion to $a_n^{\max}(t)$ and they gain their values similtaneously, we get:

$$F = \frac{c + f\rho h(g\cos\alpha - a^{\max})}{\rho h(g\sin\alpha + a^{\max})} \tag{3}$$

where $a^{\max}$ depends on earthquake magnitude or explosion charge, distance and topography. The effects of topography in 3-dimensional seismic wavefields have been simulated by (Hestholm and Ruud, 1999). At this stage of development we neglect the topography effects and directly adopt Kozyrev et al., (2000) empirical formulae for estimating $a^{\max}$ in open pit mines

$$\begin{aligned} a^{\max} &= 25.27\left(r/\sqrt{q}\right)^{-1.576}; \ \left(r/\sqrt{q}\right) \in (1 \ldots 5) \\ a^{\max} &= 3.64\left(r/\sqrt{q}\right)^{-0.38}; \ \left(r/\sqrt{q}\right) \in (5 \ldots 30) \end{aligned} \tag{4}$$

For underground explosions

$$a_c = 1302\left(r/^3\sqrt{q}\right)^{-2.93} \tag{5}$$

where r is a distance from explosion in meters and q is explosion charge in kg.

Slope angle $\alpha = \alpha(x, y)$ is obtained from

$$\cos\alpha = \overrightarrow{N} \cdot \overrightarrow{e}_3$$

where

$$\overrightarrow{N} = \frac{-\frac{\partial z}{\partial x}\overrightarrow{e}_1 - \frac{\partial z}{\partial y}\overrightarrow{e}_2 + \overrightarrow{e}_3}{\sqrt{\left(\frac{\partial z}{\partial x}\right)^2 + \left(\frac{\partial z}{\partial y}\right)^2 + 1}} \tag{6}$$

is outer normal to the surface $z(x, y)$ and $\overrightarrow{e}_1$, $\overrightarrow{e}_2$ and $\overrightarrow{e}_3$ are Cartesian unit orthogonal vectors. All calculations here are made using GMT package by Wessel and Smith (1998).

There is no precise knowledge of parameters constituting to the stability factor in eq. (3) hence its exact value can not be obtained directly. However, it may be worth to estimate directly the probability for F to be lower than some threshold F_{thr}, that is:

$$P\{F(x, y) < F_{\text{thr}}\} = \int_0^{F_{\text{thr}}} p_F(\xi) d\xi \tag{7}$$

where $p_F(\xi)$ is a probability density function (p.d.f.) of stability factor F. In general the only way to obtain p_F from arbitrary p_ρ, p_h , p_f and $p_{a_c}$is a Monte-Carlo simulating approach similar to that used in Chernouss and Fedorenko, (1998). This way is very computer intensive but hardly unavoidable to use, especially if probability densities of ρ, h, c, f and a_c are to be obtained experimentally.

For preliminary estimates of $P\{F(x, y) > F_{\text{thr}}\}$, ignoring seismic effects we have developed a simple approximation based on i) p.d.f. of h, c and f are Gaussian ii) h and c are correlated with coefficient R while c and f and h and f are mutually independent and iii) standard deviation of ρ is so small that we use a fixed value for ρ: $p_\rho(\xi) = \delta(\xi - \overline{\rho})$, $p_h(\xi) = N(\sigma_h, \overline{h})$, $p_f(\xi) = N(\sigma_f, \overline{f})$ and $p_c(\xi) = N(\sigma_c, \overline{f})$. In this formulation the stability factor F would be a sum of two random variables $\varphi = c/\rho h g \sin\alpha$ and $\psi = f \cot\alpha$. Obviously $p_\psi(x) = N(\sigma_f \cot\alpha, \overline{f}\tan\alpha)$. After some mathematical manipulations and simplifications we get the p.d.f. of the random variable φ:

$$p_\varphi(\xi) = \frac{\sigma_c \sigma_h \sqrt{1 - R^2}}{\pi(\sigma_c^2 - 2R\sigma_c\sigma_h\xi + \sigma_h^2\xi^2)} \exp\left\{-\frac{\overline{h}^2\sigma_c^2 - 2R\overline{c}\,\overline{h}\sigma_c\sigma_h + \overline{c}^2\sigma_h^2}{2(1 - R^2)\sigma_c^2\sigma_h^2}\right\}\left[1 + \sqrt{2\pi}ze^{z^2/2}F_0(z)\right]$$

where

$$\begin{aligned} F_0(z) &= \frac{1}{\sqrt{2\pi}}\int_0^z e^{-\zeta^2/2}d\zeta = \frac{1}{2}\operatorname{erf}\left(\frac{z}{\sqrt{2}}\right) \\ z &= \frac{\overline{h}\sigma_c^2 - R\sigma_c\sigma_h(\overline{c} + \overline{h}\xi) + \overline{c}\sigma_h^2\xi}{\sigma_c^2\sigma_h^2\sqrt{(1 - R^2)(\sigma_c^2 - 2R\sigma_c\sigma_h\xi + \sigma_h^2\xi^2)}} \end{aligned}$$

Finally,

$$P\{F(x, y) > F_{\text{thr}}\} = \int_{-\infty}^{F_{\text{thr}}} d\xi \int_{-\infty}^{\infty} p_\varphi(u)\, p_\psi(\xi - u)\, du \tag{8}$$

where $p_F(\xi) = \int_{-\infty}^{\infty} p_\varphi(u)\, p_\psi(\xi - u)\, du$ is calculated numerically via corresponding characteristic functions.

Summerizing the novel theoretical development presented here of our avalanche risk analysis we note that the physical snow slab model is difficult to quantify in practice simply because snow covered mountains are not considered a safe working environment in winter times. These parameters are therefore represented in Gaussian p.d.f.s while the "risk" itself is expressed as a stability factor F. This in turn becomes quite complex and a numerical brute-force Monte-Carlo simulation strategy is chosen for the p.d.f. distribution of F. Specific external loading in terms of explosions generated time histories was excluded in the above formulations but are easily incorporated through the Newark (1965) analysis scheme. The basic idea of this approach is that individual loading sources like an explosion cause internal snow slab deformation and that if this process is repeated the cumulative deformation would finally result in an avalanche triggering. Familiarity with this deformation process even if not entirely precise would add to our physical understanding of snow avalanches and this in combination with local knowledge of terrain, prevailing winds and precipitation will provide an

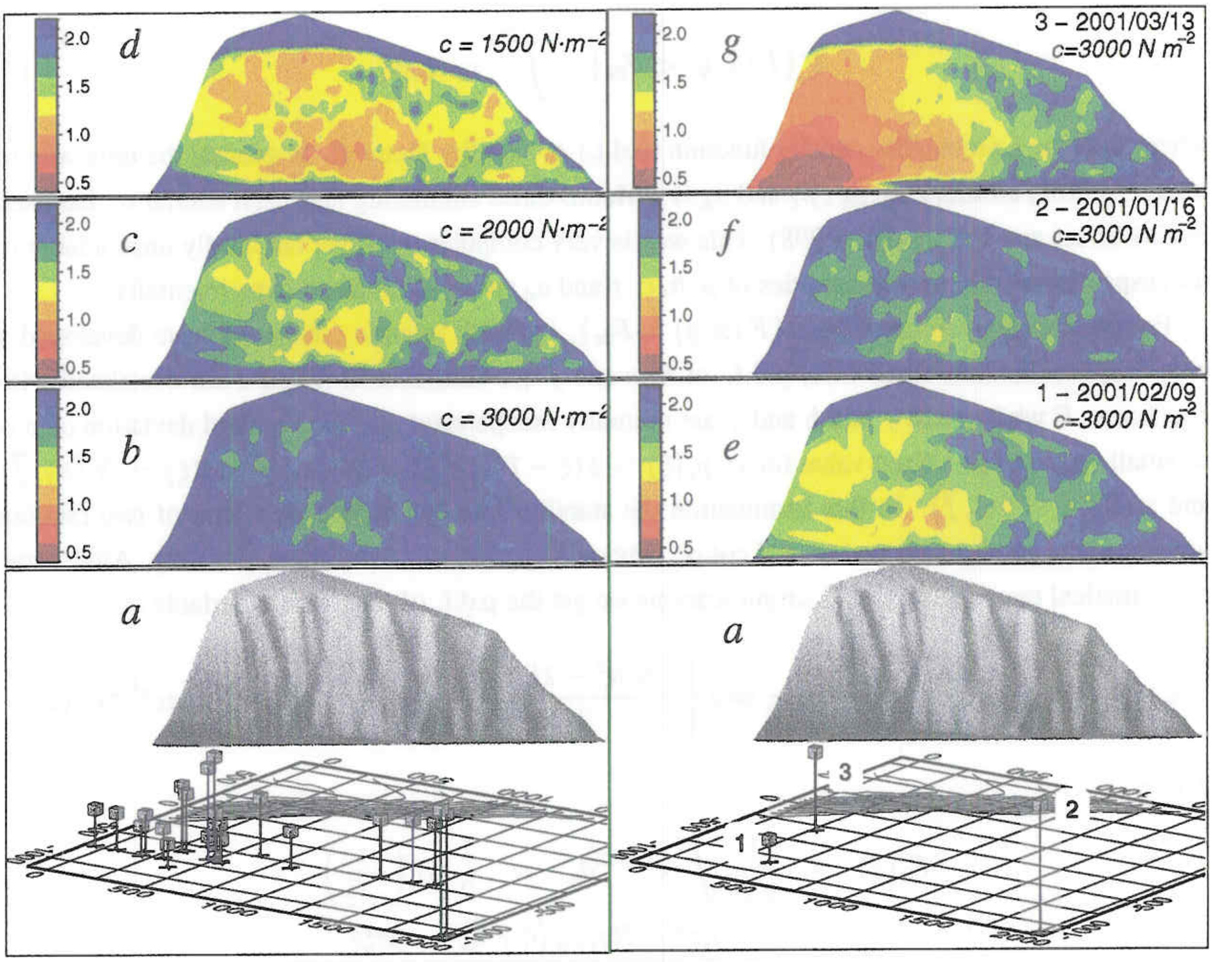

Fig. 3. Stability factor maps for different shear strength with and without seismic loading. *a* shows the avalanche starting zones with explosions made in vicinity of avalanche starting zones during the winter 2001, *b-d* represents a stability factor maps for different c, f=0.4 and ρ=300 kg/m^3 while *e-g* presents F calculated for c = 3000 n/m^2, f=0.4 and ρ=300 kg/m^3 with seismic load applied.

improved basis for in situ hazard estimates and better warnings to the public. To illustrate the theoretical developments we test the deformation concept on a mountain slope near Kirovsk (Fig. 1).

STABILITY FACTOR MAPPING

Even if seismic effects are not in action an avalanche can start due to natural reason which is degradation of lower snow layer, extensive snow thickness and so on. Fig. 3 a-d) demonstrates snow parameters influence to stability factor. We vary only shear strength c and calculate for F for $c = 3000$ $N \cdot m^{-2}$b), $c = 2000$ $N \cdot m^{-2}$(c), and $c = 1500$ $N \cdot m^{-2}$ (d). Other parameters are f=0.4, h= 1m and ρ=300 kgm^{-3}. The dangerous situation where avalanches may be triggered by seismic event is shown in Fig. 3 b, with shear strength $c = 3000$ $N \cdot m^{-2}$. At the maps (c) and (d) shear strength is small and stability factor is close to 1 or less which supposed that avalanches are released naturally and seismic load does not release vast snow mass therefore it is not as dangerous as the first case. Fig. 3 e-g) shows the results from seismic load caused by explosions which were registered by NKK station

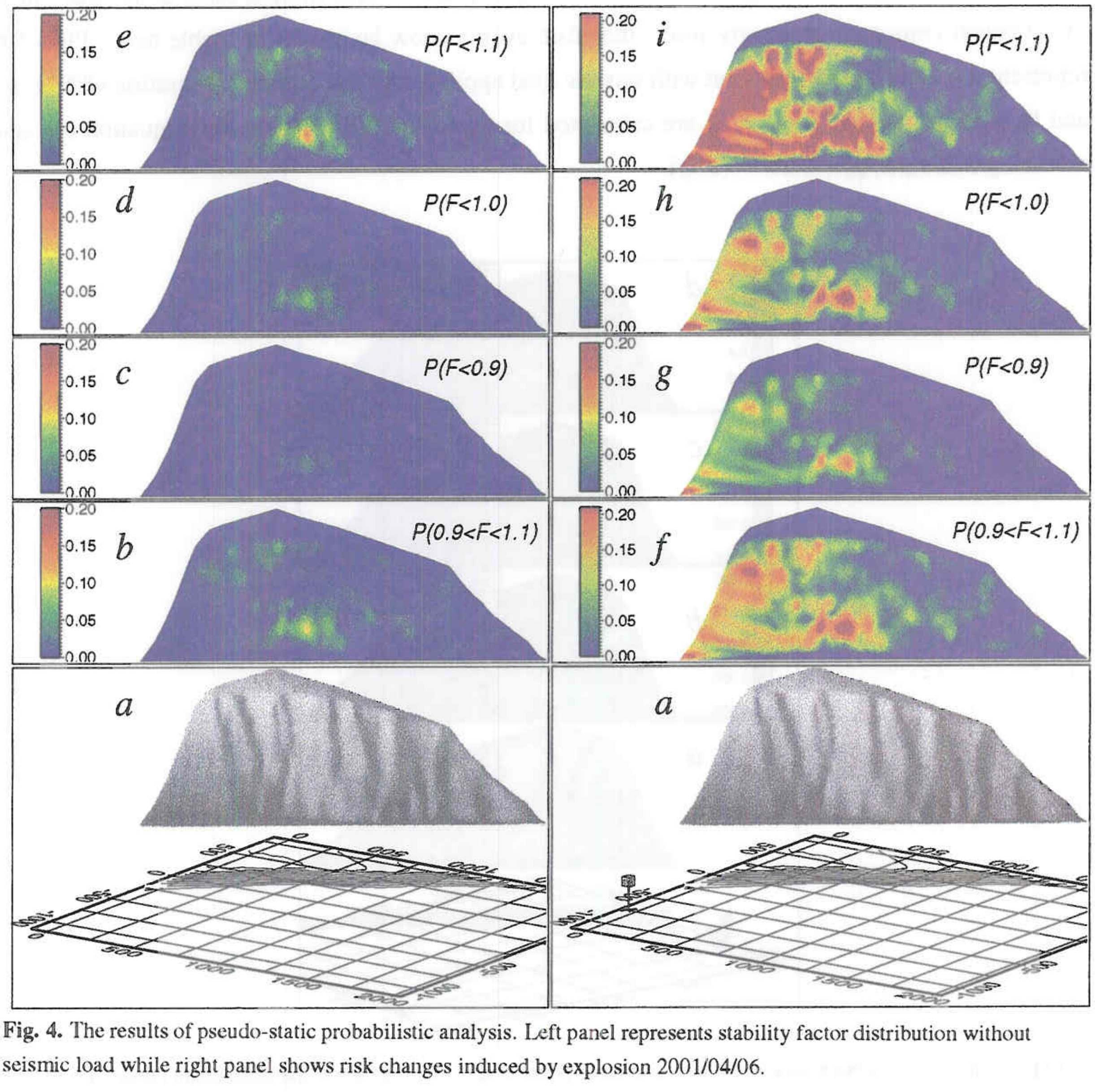

Fig. 4. The results of pseudo-static probabilistic analysis. Left panel represents stability factor distribution without seismic load while right panel shows risk changes induced by explosion 2001/04/06.

on 2001/02/09, 2001/01/16 and 2001/03/13. Stability factor F is greatly influenced by the seismic effects from these explosions. Shear strength c=3000 N $\cdot$ m^{-2} for plots (e-g) and seismic loading is evaluated using empirical equation (4).

In Fig. 4 we demonstrate an example of pseudo-static probabilistic analysis. In order to incorporate a random nature of snow parameters we assume that they are normally distributed; $\langle c \rangle$ = 3000 Nm^{-2}, σ_c= 600 Nm^{-2}; $\langle f \rangle$=0.4, σ_f= 0.08; $\langle h \rangle$=1.0 m, σ_h= 0.2 m and $\langle \rho \rangle$=300 kgm^{-3}, σ_ρ= 30 kgm^{-3}. Angular brackets indicate mean values, σ is standard deviation. Plots b-e show the probabilities $P(x,y) = P\{F(x,y) < F_{thr}\}$ where $F_{thr} = [0.9, 1.0, 1.1]$ and also $P(x,y) = P\{0.9 < F(x,y) < 1.1\}$ when the seismic loading is not involved. Notice, that $P(x,y) = P\{0.9 < F(x,y) < 1.1\}$ characterizes a most dangerous spots of factor F; small values of F indicate such places where the tangent component of gravity force dominates much over friction force. For that reason a snow layer can not hold and such places are not dangerous. Large values of F belong to places where friction force dominates much over tangent comonent of gravity force, therefore even a snow layer will be stable here. Plots f-h represent the same probabilities but with seismic load applied. The maximum acceleration $a^{\max}(x,y)$ and its standard deviation $\sigma_a(x,y)$ are calculated for explosion 2001/04/06 using equation (4) and assuming that $\sigma_a(x,y) = 0.2a^{\max}(x,y)$.

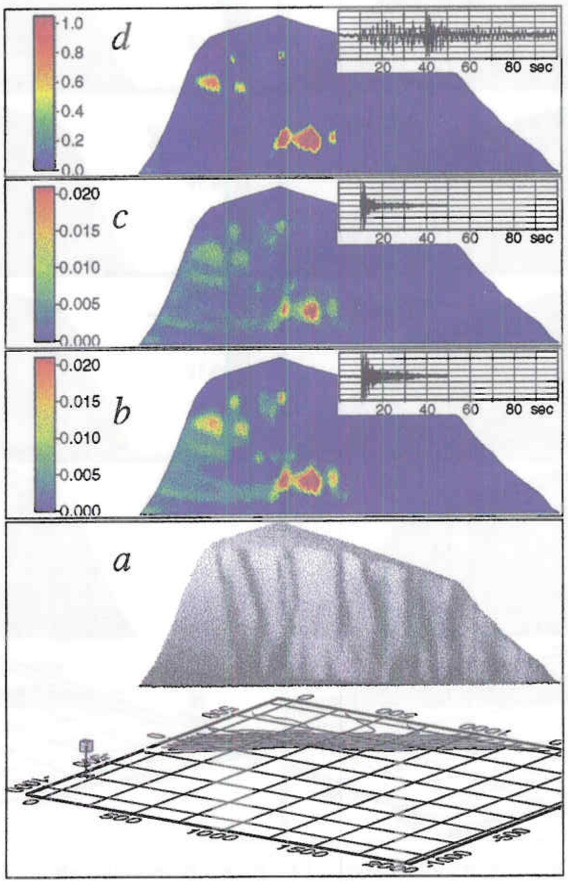

Fig. 5. Application of Newmark analysis to avalanche prone area. Color bars show displacement in meters. Inserts show seismic time histories used in calculations.

Newmark analysis requires time histories of ground acceleration. At the current stage we use some recordings from NKK, "amplifying" them according to peak ground acceleration obtained from eq.

(4). The results are shown in Fig. 5. Color bar shows displacement in meters. Notice that frequency content and duration of signal are highly significant - high frequency signals produce displacement about 0.02 m while low frequency event of longer duration yields about 1 meter with extremes over 5 meters. We use the position of explosion 2001/04/06 to calculate the spatial distribution of peak ground acceleration.

CONCLUDING REMARKS

We have invested much efforts and ingenuity in dynamic avalanche modelling and as demonstrate above very preliminary results are encouraging. In short we are able to outline a varity of "avalanche scenarios" some of which may be classed as High Risk and thus neccessiate local avalanche warnings. Needless to say, such progresses are most important to local miners and skiers in Kirovsk and adjacent Khibiny skiing resorts area.

These studies are continuing. The main efforts are applied now to find relation between snow characteristics and critical Newmark displacement results as an avalanche release probability. The data is also accumulated to derive an empirical regression equation Nemark displacement estimating as a function of shaking intensity and critical acceleration like Jibson (1995) have done for landslides. One of the future goals is estimation of input of seismisity into avalanche releasing by cannon firing or by explosives which gives an opportunity to choose places and types of the explosions for the artificial releasing more rationally. Despite common using cannon firing and explosives for artificial avalanche triggering a role of these two factors is still unstudied.

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