Russian-Norwegian project on seismicity-induced avalanches

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Abstract: Sometime a direct damage of earthquake can be less than that occurs due to triggered phenomena such as landslides, avalanches, etc. It is very difficult to get information about avalanches released by earthquakes due to their rarity. The Khibini Mountains are strongly effected by artificial seismicity caused by technological explosions in the underground mines and open pits, have 7-8 months a year avalanche period and thus are an ideal place for studies of seismicity-induced avalanches. Joint Russian-Norwegian studies were started 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 (E. Mokrov at al., ISSW'2000). To quantify seismicity a three component seismic station was deployed on the mountain top, in a few kilometers from places of explosions and a portable seismic station is used to study seismic effects in avalanche starting zones. They register the data on accelerations, velocities, displacements and their time histories. A simple physical model was chosen to analyze of snow static stability. Known by its application to seismicity-induced landslides Newmark analysis is suggested to take into account seismic influence within a dynamical model. Some estimations of the seismicity influence on snow stability for the real explosions are presented. Some possible mechanisms of influence of seismicity and air shock wave caused by explosions on snow stability are discussed. Main directions for further studies are described.

Keywords: seismisity, snow stability, avalanche, simulation.

1. Introduction

The brightest example of an earthquake-induced avalanche is Huascaran snow, ice and rock avalanche in Peru, in 1970, buried the towns of Yungay and Ranrahirca. The total death toll was tens thousand people. There are some evidences pertaining to the seismic influence on avalanche releases but this phenomenon is not well understood and any models of it are absent. In spite of enough high total frequency of earthquakes on the globe, it is very difficult to plan observational work and get comprehensive information about avalanches released by them due to their rarity in some specific avalanche prone area. 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 kilometres. An avalanche hazardous period 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 favourable 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. Data on explosion and avalanche release distributions over days of week were analyzed at the first stage. It has been shown that avalanche releases clearly correlated with explosions. To quantify underlying seismic disturbances 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 kilometres from places of explosions.

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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. 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 kilometres), trying to understand the role of seismicity 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.

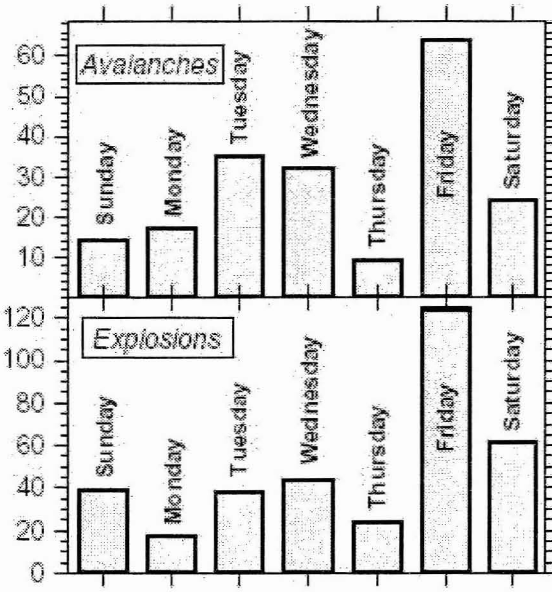

Figure 1: Number of days with avalanches and mining explosions in the Central mine area. Notice the relative large number of Friday avalanches, which is clearly correlated with the large number of explosions on Fridays that is explosions trigger

2. Statistical model

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. 1). The chi-square test has shown that these two distributions are far from independence (hypothesis of independence H0 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 H0: $R = 0$ 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 H0 of independence rejected at 1% significance level by chi-square test (Mokrov et. al, 2000). The degree of association between rows and columns in the table is 0.0427 by Kendall statistics. Thus the correlation between days of mass explosions and avalanche releases is enough clear to be recognised but it is too weak to be used for avalanche prediction.

3. Physically-based models

3.1 Pseudo-static model

Seismisity-induced avalanches occur when the sum of static and inertia forces acting on a snow layer element exceeds the friction and cohesion forces between element and the underlying body (boundary forces are not considered). The latter is also normally snow or ice stemming from snowfalls in the autumn. A condition for snow layer pseudo-static stability may be written as

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

where: ρ- snow density; h is snow thickness; α - slope angle; f - friction coefficient between snow element and layer below; c - shear strength; g - gravity acceleration; a_τ tangential acceleration of external load (usually seismicity-induced) directed along the underlying surface downwards; a_n - same as a_τ but directed upwards normally-to-surface. With this condition a stability factor F is defined as:

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

If $F>1$ snow is stable. Real observations imply that violation of this condition is necessary but not sufficient for an avalanche to occur. Sometime accelerations a_τ and a_n act during a very short time and an internal slab deformation caused by them is not sufficient for avalanche release. The time span over which these deformations accumulate depends naturally both on magnitude and duration of the external loading. One of the ways giving an opportunity to calculate them is a dynamical approach originally developed by Newmark (1965) and more recently applied by Jibson (1993) for landslides.

3.2 Dynamic model

The sliding mass is assumed to be a rigid block as in the described above model. Let for simplicity $a_\tau = a_n = a$ (as NKK measurements show it is enough correct assumption). Down slope deformations occur during the time periods when the induced peak ground acceleration within the slide mass $a(t)$ exceeds the critical acceleration a_c (Fig. 2)

$$a_c = \frac{c + \rho hg(f\cos\alpha - \sin\alpha)}{\rho h(1+f)} \tag{3}$$

In general, the smaller the ratio (below 1.0) of a_c to a, the larger are the number and duration of times when down slope movement occurs, and thus the greater is the total amount of this movement. The amount of down slope movement also depends on the duration or number of cycles of ground shaking. The value of cumulative displacement d is a criterion of snow stability in this approach. A threshold value d_{thr} can be determined from observation for avalanche releases and seismicity.

5. Stochastic simulation

There is no precise knowledge of parameters constituting to the stability factor in eq. (2) or displacement d in Newmark analysis, hence their exact

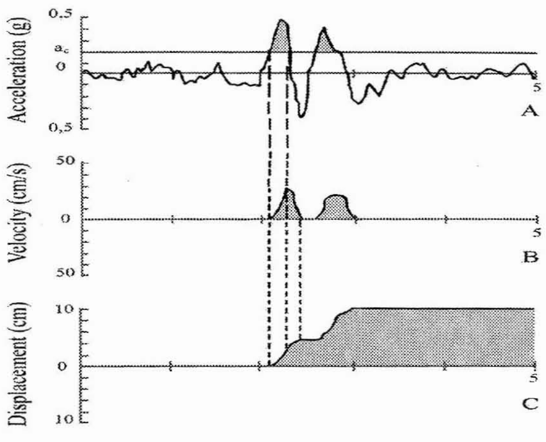

Figure 2: Demonstration of the Newmark-analysis algorithm (adapted from Wilson and Keefer, 1983). A, Earthquake acceleration-time history with critical acceleration a_c (horizontal dashed line). B, Velocity of landslide block versus time. C, Displacement of landslide block versus time.

values 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:

$$P\{F(x,y) < F_{thr}\} = \int_0^{F_{thr}} p_F(\xi)d\xi \tag{4}$$

Where $p_F(\xi)$ is a probability density function (p.d.f.) of the stability factor F. Or for dynamic model

$$P\{d(x,y) < d_{thr}\} = \int_0^{d_{thr}} p_d(\xi)d\xi \tag{5}$$

Where $p_d(\xi)$ is p.d.f. of the cumulative displacement d. In general the only way to obtain p_F from arbitrary p_ρ, p_h, p_f and p_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 are to be obtained experimentally.

4. Numerical experiments

A few numerical simulations of seismic influence on snow stability in avalanche starting zones were carried out with data of real explosions in the Central mine open pit. Relief was represented with digital elevation model. Kozyrev's at al (2000) estimations of peak ground accelerations due to explosions in open pits were used in pseudo-static model.

$$a^{\max} = 25.27(r/\sqrt{q})^{-1.576}; (r/\sqrt{q}) \in (1...5)$$
$$a^{\max} = 3.64(r/\sqrt{q})^{-0.38}; (r/\sqrt{q}) \in (5...30) \quad (6)$$

Where $a^{\max}$ – peak ground acceleration in ms^{-2}, r – distance from explosion in m and q – explosion charge in kg. In deterministic simulation such values of the parameters: c = 3000 N m^{-2}; f = 0.4; h = 1m and ρ = 300 kgm^{-3} were taken. In order to incorporate a random nature of snow parameters that was assumed that they are normally distributed; $\langle c\rangle = 3000$ Nm^{-2}, $\sigma_c = 600$ Nm^{-2}; $\langle f\rangle=0.4$, $\sigma_f = 0.08$; $\langle h\rangle=1.0$ m, $\sigma_h = 0.2$ m and $\langle\rho\rangle=300$ kgm^{-3}, $\sigma_\rho = 30$ kgm^{-3}. Angular brackets indicate mean values, σ is standard deviation. Newmark analysis requires time histories of ground acceleration. At the current stage there were used some recordings from NKK, "amplified" according to peak ground accelerations obtained from eq. (6). Some results of the simulation are presented below. 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 F for $c = 3000$ Nm^{-2}, $c = 2000$ Nm^{-2}, and $c = 1500$ Nm^{-2}. 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 $c = 3000$ Nm^{-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 on 2001/02/09, 2001/01/16 and 2001/03/13. Stability factor F is greatly influenced by the seismic effects from these explosions. In Fig. 4 we demonstrate an example of pseudo-static probabilistic analysis. 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 the 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 component of gravity force, therefore even a thick 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

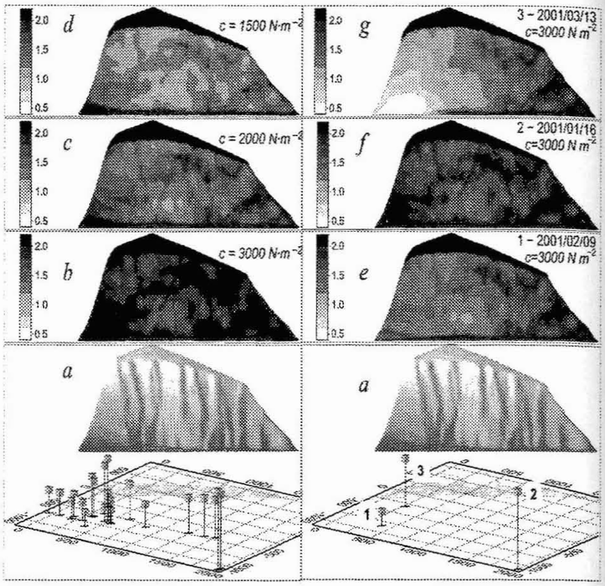

Figure 3: Stability factor maps for different shear strength with and without seismic loading. a shows the avalanche starting zones with explosions made in vicinity of avalanche starting zones during the winter 2001, b-d represents a stability factor maps for different c, while e-g presents F calculated for c = 3000 n/m2, with seismic load applied.

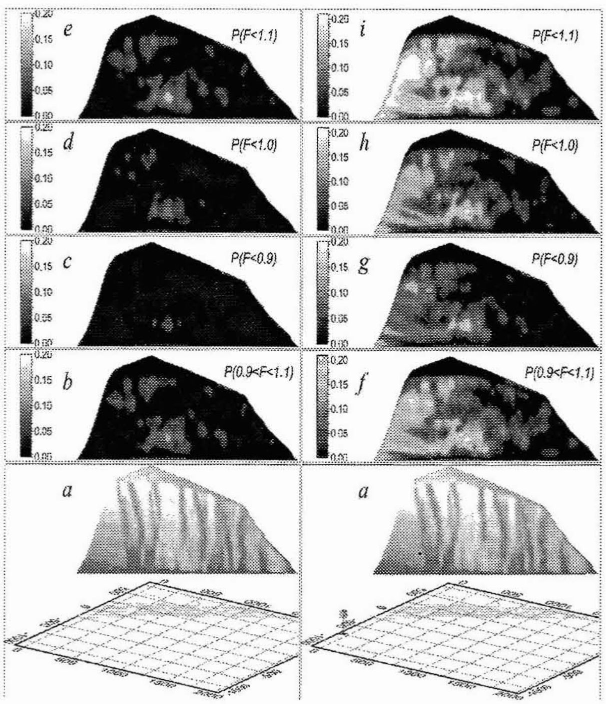

Figure. 4: The results of pseudo-static probabilistic analysis. Left panel represents stability factor distribution without seismic load while right panel shows risk changes induced by explosion 2001/04/06.

2001/04/06 using equation (6) and assuming that $\sigma_a(x; y) = 0.2a^{max}(x; y)$. 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. (6). The results are shown in Fig. 5. 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 m with extremes over 5 m. We use the position of explosion 2001/04/06 to calculate the spatial distribution of peak ground acceleration.

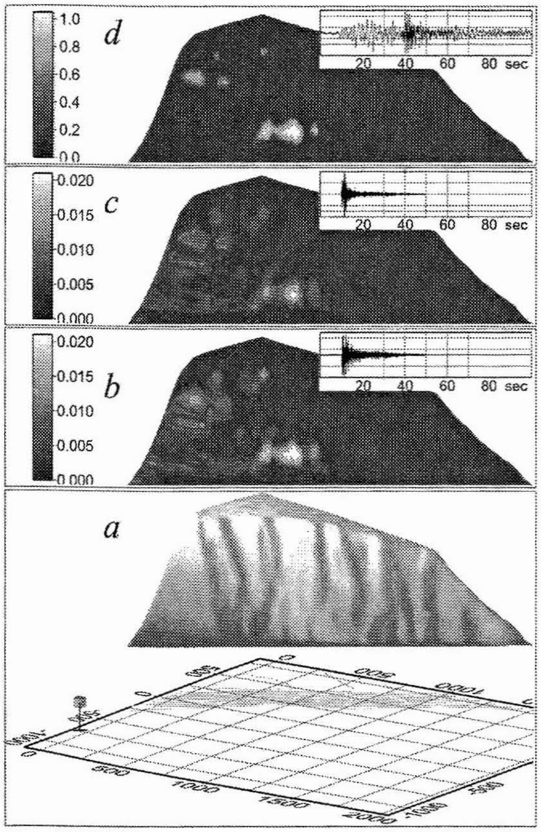

Figure 5: Application of Newmark analysis to avalanche prone area. Color bars show displacement in meters. Inserts show seismic time histories used in calculations.

6. Explosions and artificial avalanche release

There is enough long history of explosion using for artificial avalanche release. It is a main and almost single method for preventive avalanche release. Till the last time at the best only conceptual models of explosion influence on snow cover stability existed, but practice needs the verified numerical models taking into account all aspects of explosion using for the most effective application this method. There are at least two kinds of explosion influences on snow cover stability: artificial seismicity and air shock wave caused by explosions. The second one gives a down slope impulse component to snow if the explosion occurs in snow and. can not decrease snow stability within the model considered above if the explosion occurs over snow cover, since extra air pressure just increases normal loading and therefore friction force. Both of these effects can also crash a weak layer structure that may decrease shear strength – c. The influence of ground shaking on shear strength in soil is known. It is very probable that mechanical parameters of a weak snow layer are changed when elastic waves pass trough it due to break of contacts between snow particles (see fig. 6). Next studies in continuation of the project should quantify this effect.

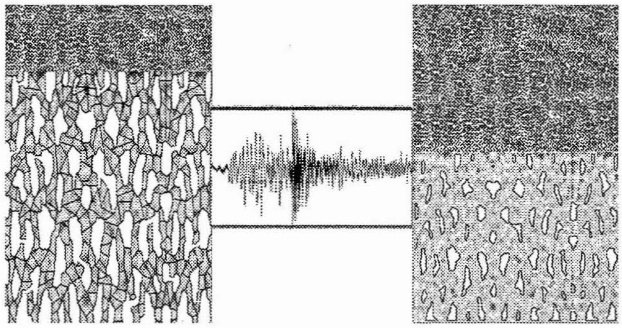

Figure 6: Hypothetical schema of the weak layer compaction and strength decreasing due to break of contacts between snow particles at shaking.

7. Concluding remarks

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 for Nemark displacement as a function of shaking intensity and critical acceleration like Jibson (1995) have done for landslides. At this stage of studies we neglect the topography effects and directly adopt Kozyrev et al., (2000) empirical formulae for estimating a^{max} in open pit mines. The effects of topography in 3-dimensional seismic wave fields have been simulated by Hestholm and Ruud, (1999) and we are going to use this model for spatial-temporal estimations of explosion induced accelerations. One of the future goals is estimation of input of seismicity 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. Of course the results of such studies will be incomplete if the effects of air shock wave are not taken into account. Studies of them are considered as continuation of the seismic ones to describe all mechanisms of explosion influence on snow stability.

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References

Chernouss, P. and Fedorenko, Yu. (1998) Probabilistic Evaluation of Snow Slab Stability on Mountain Slopes. *Annals Glaciology*, Cambridge, UK, v. 26, p 303-306.

Chernouss, P., Zuzin, Yu., Mokrov, E., Kalabin, G., Fedorenko, Yu. and Husebye, E. (1999) Avalanche Hazards in Khibiny Massif, KOLA, and the new Nansen Seismograph Station. *IRIS Newsletter*, No. 1, p. 12-13.

Fedorenko, Yu., Husebye, E. and Boulaenko, E. (2000) School Yard Seismology, *Orfeus Newsletter*, Vol. 2, No. 3, p 22.

Hestholm, S. O., and Bent O. Ruud. (1999) Three-dimensional finite difference viscoelastic wave modeling including surface topography. *Geophys. J. Int.* 139, p. 852-878.

Jibson, R.W., 1993, Predicting earthquake-induced landslide displacements using Newmark's sliding blok analysis: Transportation Research Record, no. 1411, p. 9-17.

Kozirev, S., Lukichev, S., Fattahov, E., and Kershinsky, A. (2000) "Instrukciya po raschetu seismicheski opasnih zon ot podzemnih massovih vzrivov i vzrivov v kar'ere dlya poverhnostnih sooruzhenii, gornih virabotok i bortov ustupov". Kirovsk-Apatity, 2000, (KNC Gorny Institut, OAO "Apatit"), 36 p.

Mokrov, E., Chernouss, P., Fedorenko Yu. and Husebye, E. (2000) The Influence of Seismic Effect on Avalanche Release. Proc. Int. Snow. Sci. Workshop ISSW-2000. Big Sky MT. USA, Oct. 2000, p. 338-341.

Newmark, N. M. (1965) Effects of earthquakes on dams and embankments: *Geotechnique*, 15, No. 2, p. 139-160.

Wessel, P., and Smith, W. H. F. (1998) New, improved version of the Generic Mapping Tools Released, *EOS Trans.* AGU, 79, 579.

Wilson, R.C., and Keefer, D.K., 1983, Dynamic analysis of a slope failure from the 6 August 1979 Coyote Lake, California, earthquake: Bulletin of the Seismological Society of America, v. 73, p. 863-877.