A STUDY OF BLASTING -INDUCED SNOW INSTABILITIES AND AVALANCHE RELEASES

Pavel Chernouss[1,3], Yuri Fedorenko[2], Nikolai Barashev[1], Evgeny Mokrov[1]

[1)] Centre for Avalanche Safety, "Apatit" JSC, e-mail: pchernous@apatit.com
[2)] Polar Geophysical Institute, Russian Academy of Sciences
[3)] Murmansk State Technical University

Abstract
It is known that explosions can trigger avalanches but mechanisms of their influence remain unstudied and experimental data on explosion effects on the snow cover stability are very poor. The study deals with explosion factors such as seismic and air shock waves. Two mechanisms of snow instability caused by blasting are discussed. One of these is connected with additional load on snow layer and the other - with a snow strength decrease. Presented are the equipment for ground shaking and air shock wave pressure measurements as well as the analysis of the technological explosions measuring results from an open pit mine. Described are the construction and the characteristics of a shaking table designed to study the shaking effect on snow strength in laboratory Consideration is given to the approaches to deterministic and stochastic simulation of blasting effects on snow stability and avalanche release. The study was supported by the Russian Foundation for basic research (grant 05-05-64368-a).

Key words: explosions, seismicity, air shock waves, avalanches, simulation

1. INTRODUCTION
It is generally accepted that not only explosions but just loud sounds can cause an avalanche release. Nevertheless, there are no methods to quantitatively assess this effect. Recent studies (Mokrov et al., 2000) have shown that there is a weak but statistically significant dependence of avalanche releases on technological blasting at mines. Blasting itself is a single and the most effective method of preventive avalanche release. In spite of widely spread and effective use of blasting in preventive avalanche release, physical mechanisms involved in avalanche triggering remain unclear. This vagueness is an obstacle preventing the incorporation of explosion effects into avalanche forecast models and rationalization of the methods of artificial avalanche release.
At least, three explosion factors influence the snow stability, namely: i) ground shaking, ii) air shock waves impacting the snow surface and iii) direct snow "push" caused by the explosion, as shown in Figure 1.
In general, air shock waves produced by explosions (rarely by supersonic planes) have a rather limited area of influence but ground shaking caused by earthquakes can effect rather large areas. Sometimes a direct damage caused by earthquakes can be less than that occurred due to triggered phenomena such as tsunamis,

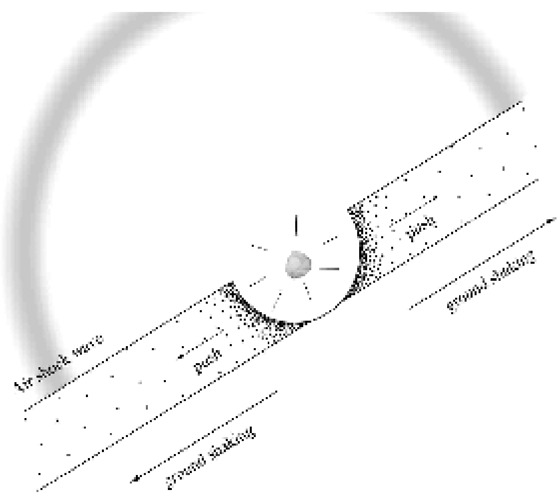

Figure 1. A common schema of main explosion factors influencing on snow stability.

landslides, avalanches, etc. There are some evidences pertaining to seismic influence on avalanche releases but this phenomenon is poorly studied and there are no even conceptual models. In spite of high rate of occurrence of natural earthquakes over the globe, it is very difficult to plan observational work and get comprehensive information about avalanches released by them due to their rare occurrence in any avalanche prone area specially selected for studies. Fortunately, artificial earthquakes caused by explosions may be used as an analogue of natural ones. The Khibini mountains in Arctic Northwest of Russia is a very suitable area for such studies because they are strongly affected by artificial seismicity caused by blasting in underground mines and open pits of “Apatit” mining company, with avalanche period lasting here for about eight months a year. Blasting charges vary from tens kilograms to hundreds tons and the number of blasts makes up some hundreds per winter. Depending on the charge, the distance to avalanche prone areas and on some other factors, blasting can cause very intensive ground shaking comparable with earthquakes of 6-7 according to modified Mercalli intensity scale. Blasting in the open pit mines is also accompanied by strong air shock waves. “Apatit” mining company has a special unit – the Centre for Avalanche Safety (CAS) – whose activity is oriented to avalanche prevention and study. CAS was founded in 1936 and since that time has accumulated a lot of data on released avalanches. These circumstances explain why the Khibini mountains have been selected for experimental studies of blasting effects on snow stability and avalanche release. The goals of the studies were outlined as: 1. to quantitatively characterise the correlation between seismic events and avalanche releases; 2. to collect data on the ground shaking and air shock wave characteristics, which are caused by blasting 3. to describe snow strength behaviour under short-term pulse load and shaking; 4. to develop models to show snow instability appearance and avalanche release, which are caused by seismicity and air shock waves. An ultimate goal of the studies is to improve the assessment of the earthquake or blasting -induced avalanche risk and develop rational methods of preventive avalanche release by blasting The first project was launched by CAS, Kola Science Centre of Russian Academy of Sciences jointly with University of Bergen in 1999. A comparison of day-of-week distributions of blasting and avalanche releases for two regions - an open pit and underground mines - showed (Mokrov *et al*., 2000) that they are interdependent (the hypothesis of independence H_0 should be rejected at a 1% significance level). The correlation between days with blasting and avalanche releases is clear enough to be recognised but it is too weak to be used in avalanche prediction. Physically-based models have to be developed and applied for this purpose. To supply the models with data on ground shaking and air shock waves, special seismic measurements were organised together with Murmansk State Technical University. Simultaneously, seismicity-induced snow instability and avalanche release simulation was initiated. The work on construction of a shaking table to study seismic effects on snow strength in laboratory was started two years ago. The goals of the present study are to describe activity in the fields mentioned above and present the results of the field ground shaking and air shock wave measurements, which are induced by blasting in an avalanche prone area, and some physically based approaches, taking into account their influence on snow stability.

2. MEASUREMENTS

2.1 *Seismic measurements*

First 3-component measurements of ground acceleration, velocities and displacements were started at the Nansen seismic station (Chernouss et al., 1999) installed on a mountain plateau few kilometres from the blasting sites. These characteristics were measured later with portable stations in the adjacent to blasting sites area (Figure 2). The stationary Nansen seismic station is equipped with three standard Russian seismic sensors SM-3KV. The portable station Cossack Ranger (Figure 3) employed geophones GS-11D, Geospace Corp., Huston as seismic sensors (Fedorenko et al., 2000). It is possible to plug some 3-component sensors simultaneously to the portable station. The acceleration measurement results for both stations are identical in the range from 0.5 to 40 Hz. For the measurements in the nearest to the blasting area, a standard accelerometer DS-477 (BLASTMATE, Ontario, Canada) was also used. The accelerometer is supplied with a microphone to measure air shock wave pressure (Figure 4).

The measurements showed that the duration of the seismic signals caused by blasting depends on the amount of explosive, spatial distribution of charges, type of blasting (aerial or underground), etc**.** and varies from 2-3 seconds to 10 seconds, and even more. Maximum registered acceleration was 8,7 m/s^2 for DS-447 and 1.2 m/s^2 for Cossack Ranger. This difference may be explained by difference in frequency characteristics between the stations (0.5 – 100 Hz for Cossack Ranger and 2 – 250 Hz for DS-477).

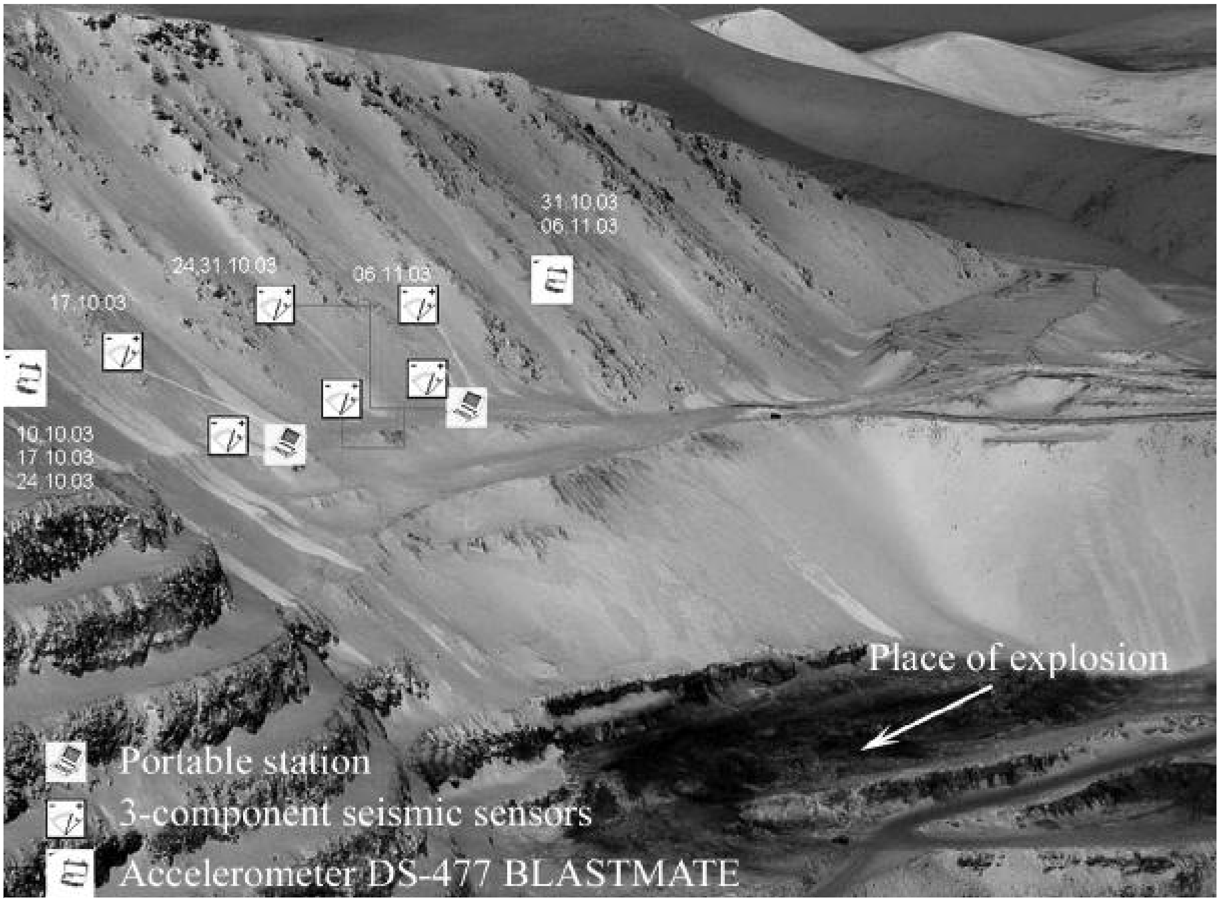

Figure 2. Picture of the avalanche sites with places of measurement sites and a part of the Central open pit mine with places of explosions.

Figure 3. Portable seismic station Cossack Ranger.

At a great distance from explosions, the measured accelerations are similar for both stations. Empirical dependence of peak ground acceleration - a^{max} (m/s^2) on mass of charge – q (kg) and distance – r (m) to explosion obtained with DS-477 (Kozyrev et al., 2000) for open pit mines is:

$$a^{max} = 25.27\ (r/q^{0.5})^{-1.576};\ (r/q^{0.5}) \in (1…5) \quad (1)$$

$$a^{max} = 3.64\ (r/q^{0.5})^{-0.38};\ (r/q^{0.5}) \in (5…30) \quad (2)$$

while for underground explosions

$$a^{max} = 1302\ (r/q^{0.33})^{-2.93} \quad (3)$$

High frequency oscillations are rapidly decreasing with a distance. Oscillations in 1 … 5 Hz frequency range may exceed 0.1g in the vicinity of explosion zone (hundreds meters for the Khibini blasting

For some seismic events, the accelerations were measured simultaneously on the rock and snow surface (Figure 5). The measurements showed that at low frequencies, the signals are very similar while at high frequencies, they are significantly different (Figure 6). This effect

Figure 4. Accelerometer DS-477

reveals the effective absorption of seismic energy in a thin snow layer at higher frequencies.

The probability density functions of seismic signals (acceleration, velocity and displacement amplitudes) were normal or very close to normal (Figure 7). This fact is important for mathematical simulation of seismic influence on snow stability.

2.2 *Acoustic measurements*

Acoustic measurements were carried out with accelerometer DS-477 simultaneously with seismic measurements during blasting in the open pit. There were made some records of air shock wave extra pressure for different blasting. An example of the record is shown in Figure 8. Distances from blasting on to the DS-447 varied from 350 m to 1600 m. The duration of acoustic signals caused by blasting depended on the amount of explosive, spatial distribution of charges, etc**.** and varies from 0.5 to 4 seconds. Maximum registered extra pressure was equal to 324 Pa.

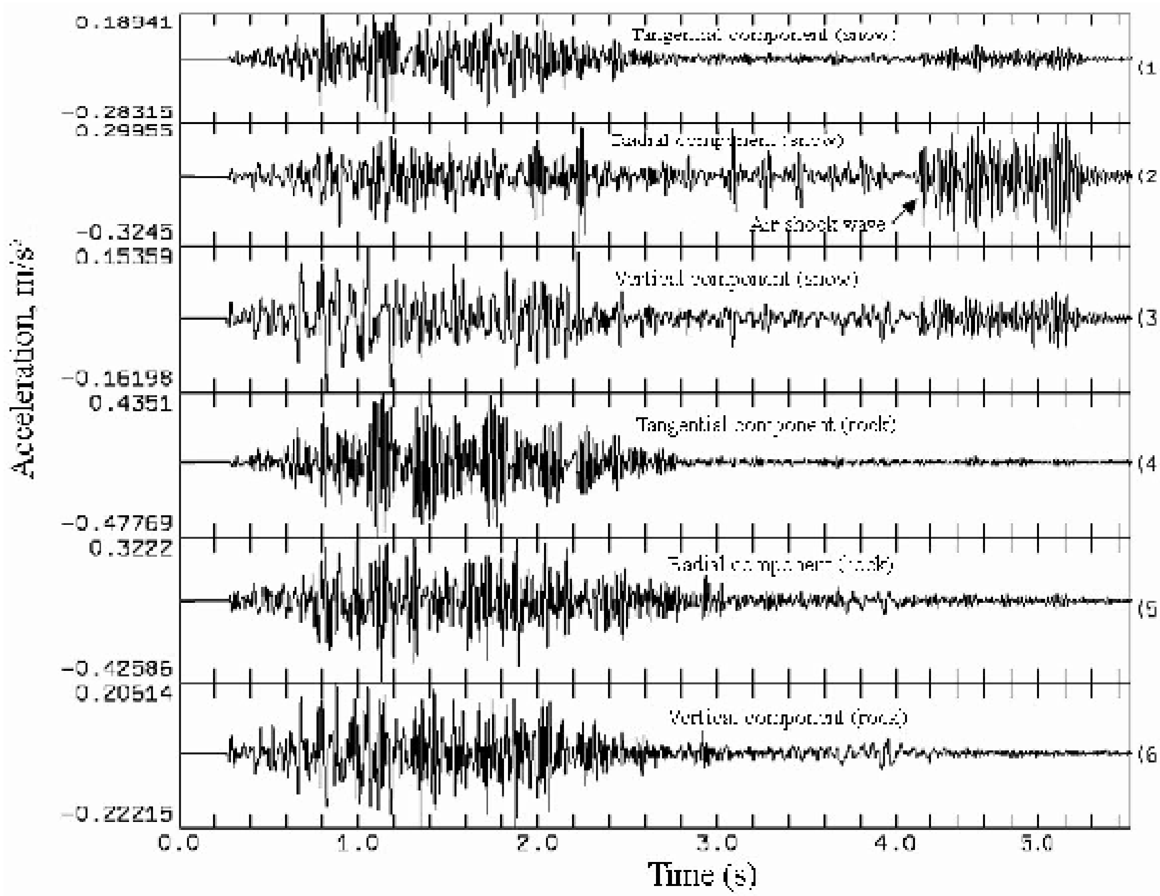

Figure 5. An example of acceleration records for snow surface and underlying surface (rock).

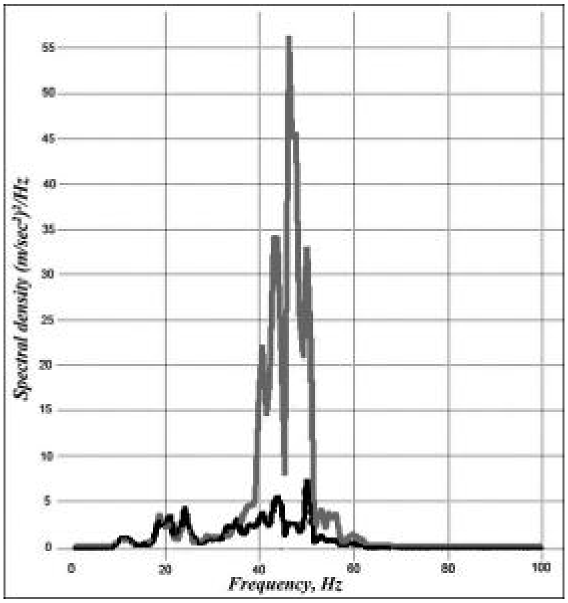

Figure 6. Spectrum of the radial component of acceleration for the seismic event on 24.10.03. Grey line – rock, black line – snow.

3. INSTABILITY SIMULATION

There were considered two approaches for seismicity-induced snow instability and avalanche release simulation – static and dynamical (Chernouss *et al*., 2002, Fedorenko *et al*., 2002). In the static approach, taking into account the underlying surface shaking (seismicity), a snow slab element on the slope is represented as a solid block subjected to gravity, friction, cohesion and inertia forces. The condition for the block static stability may be shown as

$$rh(g\sin a + a_t < c + frh(g\cos a - a_n) \quad (4)$$

Here g is gravity acceleration; a_τ – tangential acceleration (positive acceleration is directed along the underlying surface downwards); a_n – acceleration normal to the underlying surface (positive acceleration is directed normally upwards); ρ – snow density; c – shear strength; f – friction coefficient between the snow element and the underlying surface; h – snow thickness; α – slope inclination. The relationship between sum of keeping forces and shearing ones is the stability factor F (Chernouss *et al.,* 2002 and Fedorenko *et al.,* 2002).

$$F = \frac{c + frh(g\cos a - a_n)}{rh(g\sin a + a_t)} \quad (5)$$

The snow block is stable if F > 1, and unstable if F ≤ 1. Generally speaking, a_n and a_τ may have different values, even different signs, but in most cases we observed the maximum values of a_n and a_τ closely correlated and were approximately equal to each other. It is possible to use $a_n = a_\tau = a^{max}$ for the worst case, a^{max} is maximum acceleration for a seismic event. The acceleration depends on the earthquake magnitude or on the blasting charge, distance and topography (see equations 1-3). Since there is no precise knowledge of parameters constituting the stability factor and hence the exact value of this factor can not be obtained directly. However, it may be worth of estimating directly the probability that F will be lower than some threshold value F_{thr}, that is:

$$P\{F(x,y) < F_{thr}\} = \int_0^{F_{thr}} p_F(x)dx \quad (6)$$

where $p_F(\xi)$ is a probability density function of stability factor F. In general the only way to obtain p_F for arbitrary p_ρ, p_h, p_c and p_a is a Monte-Carlo simulation. A similar approach was used by Chernouss and Fedorenko (1998) to estimate spatial distribution of avalanche release probability. This way is computationally intensive but hardly unavoidable to use, especially if it is necessary to use experimentally obtained probability densities of ρ, h, c and a which do not belong to the theoretical distributions. The results of evaluation of stability factor probabilities can be presented as maps that show stability changing due to seismic effects (see Figure 7).

As it was mentioned, if F>1, the snow is stable. In situ observations show 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 period of time and an internal slab deformation caused by them is not sufficient for avalanche release. The time span, over which these deformations accumulated to a critical value, depends naturally on both value and duration of the external load. 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. The Newmark model calculates stepwise displacement of snow relative the underlying rock (Figure 8) and compares it with a critical value. A critical displacement is used as a criterion of avalanche release in this approach. The same way as it

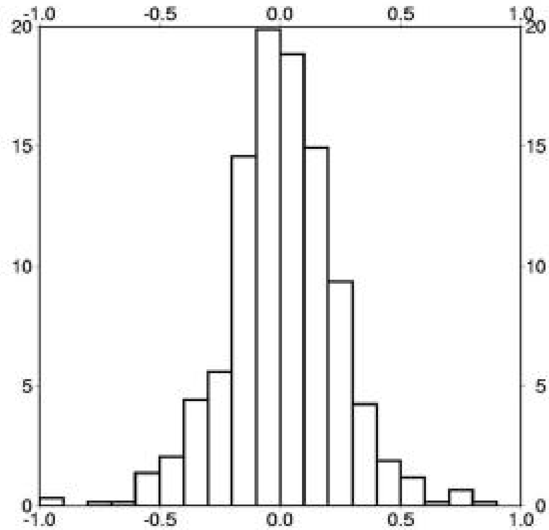

Figure 7. Histogram of the normalized acceleration (in %) for the first three second of the seismic event 31.10.03.

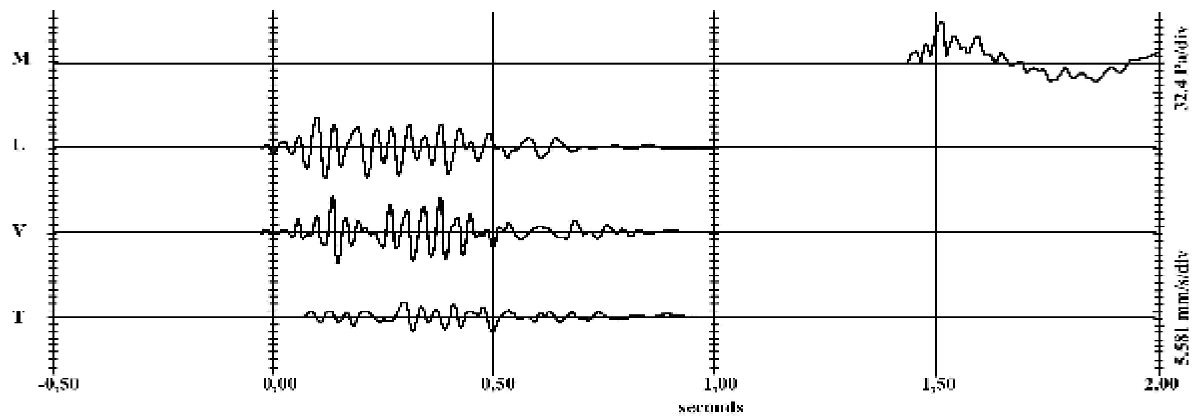

Figure 8. Record of explosion in the open pit: M - acoustic component (extra pressure); L, V and T – seismic components (velocity).

was done for the stability factor or its probability the Newmark displacement can be mapped to reveal sites where snow stability is mostly affected by seismicity (Figure 9).

The values of critical Newmark displacement for different types of snow can be obtained from measurements of snow characteristics in fracture lines for seismicity-induced avalanches or from laboratory experiments. The same approaches as for seismicity can be applied to take into account air shock wave influence on snow stability. Essential difference is in that the air shock wave produces only normal load on a snow pack that can not produce deformation along the slope. Other mechanisms of instability are likely to exist. For example, both seismic and acoustic effects can crash the underlying weak layer structure, which may decrease shear strength – *c*.

4. TESTS IN LABORATORY

A review of the existing shaking tables showed that they have no required technical characteristics or bulky, complicated in mounting and adjustment, being not adaptable for operation in field conditions and, above all, are very expensive. These circumstances forced us to create a shaking table especially for such type of experiments. Two shaking tables were designed and constructed to study the mechanism of instability appearance induced by possible snow strength change caused by vibration. The first designed table (Figure 10) can produce periodic oscillations with frequencies from 1 to 40 Hz and accelerations from 0.001 to 2 m/s^2. There was also an opportunity to produce short-term damped oscillations by shock loading (Figure 10). A measuring system for the table was based on that developed for the portable seismic station. Special software gives an opportunity to display shaking parameters, such as frequency and acceleration. The table was enough big, heavy (50 kg, together with snow sample) and could not produce polarised oscillations. Nevertheless, it was possible to carry out some experiments with new snow that revealed the effect of snow shear strength decreasing due to shaking of the underlying surface. For example, during the experiments with new snow of 110 kg/m^3 in density under vibration of 15 Hz, normal pressure of $4.9*10^2$ Pa with peak acceleration 0.3 m/s^2 shear strength was reduced in three times practically immediately after shaking initiation. Since the experiments were carried out with natural snow at the field station of CAS on

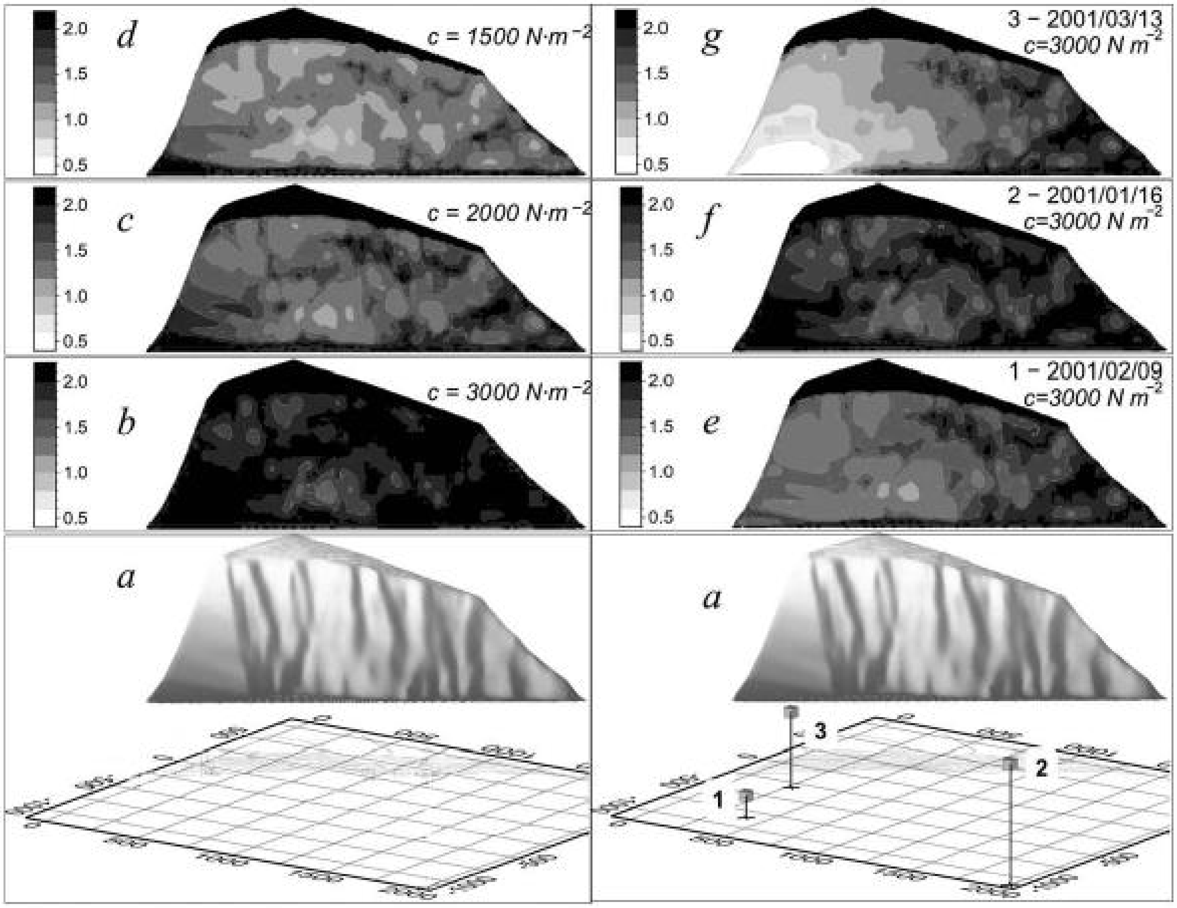

Figure 9. The static probabilistic analysis results. A left-hand panel represents the stability factor distribution with no seismic load while a right-hand panel demonstrates risk changes induced by the explosion dated by 04/06/2001. F is the stability factor. $F > 1$ for a stable snow pack and $F < 1$ – for an unstable snow pack (Chernouss et al., 2002).

the mountain plateau, the accuracy was rather low, mainly due to spatial variability of shear strength. A new shaking table was made in 2005. It is more compact (Figure 11), has the same characteristics of shaking as the previous one and can produce polarised oscillations for better understanding of influence of different types of seismic waves on snow strength. The table is easy to transport and there is an idea to use it in experiments with artificial snow in cold chambers to avoid its spatial inhomogeneity peculiar to natural snow.

5. CONCLUDING REMARKS

The results of studies obtained at this stage make mechanisms of seismicity-induced avalanche releases more clear. It is possible, at least, relatively, to evaluate the spatial distribution of seismic effects on snow stability on a mountain slope and avalanche release possibility. We used empirical equations to assess ground shaking caused by explosions, but for earthquakes the physically-based numerical models could be also used for this purpose (Hestholm and Ruud, 1999).

The studies are in progress in some directions. Some efforts are applied now to obtain field data and find relations between snow characteristics and critical Newmark displacement results as an avalanche release probability. The data is also accumulated to derive an empirical regression equation estimating Nemark displacement as a function of shaking intensity and critical acceleration, like Jibson (1995) has done for landslides.

The main attention in the nearest future will be paid to experimental studies into seismic effects on snow strength. The studies will be carried out with natural snow and, if we find an opportunity, with artificial snow

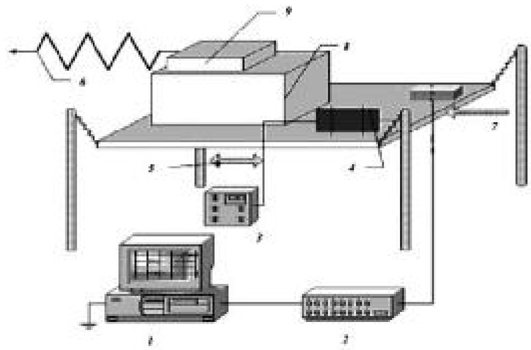

Figure 10. A sketch of the installation for simulation of seismic vibration and its influence on snow shear strength. 1. Computer; 2. ADC; 3. Frequency regulator; 4. Vibrator; 5. Periodic oscillations; 6. Constant shear load; 7. Short impulse shock load; 8. Snow block; 9. Shear frame; 10. Seismic sensor (accelerometer). It is also possible to simulate static and dynamic normal loading.

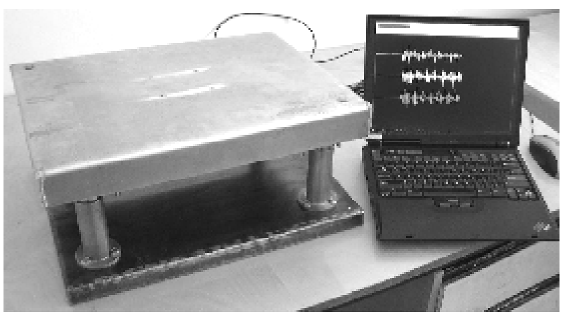

Figure 11. The results of static probabilistic analysis. Left panel represents probability distribution of stability factor without seismic load while right one shows the distribution under seismic loading induced by explosion.

The improvement of snow instability simulation will be made with application of a Monte-Carlo method including stochastic simulation of seismic shaking of the underlying surface.

Since the data allowing control over snow stability on the mountain slope are spatially distributed, it is convenient to use GIS to simulate snow instability appearance and avalanche release and visualisations of the results.

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