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Report

Studies of seismic effects on snow stability on mountain slopes

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Abstract: Studies of seismicity caused by technological explosions at mines in the Khibini Mountains and its influence on snow stability and avalanche releases began five years ago. First quantitative assessments of such influence were obtained during this time. It has been shown that there is a statistically significant correlation between seismic events and avalanche releases. Special seismic measurements to evaluate shaking effects of explosions have been carried out. The most interesting results of the measurements are described. At least two factors caused by shaking decrease snow stability–1) Inertia (decreases friction and increases downhill force), and 2) Snow strength decrease. Deterministic and stochastic models describing the influence of the first factor are presented. A shaking table designed to study seismic influence on snow shear strength, as well as first results obtained with it, are described. Directions of future studies are outlined. The work was supported by RFBR grants: 04-05-65057-a; 05-05-64037-a; 05-05-64368-a.

key words: seismicity, snow stability, avalanche release

1. Introduction

Sometimes direct damage caused by an earthquake can be less than that due to triggered phenomena such as tsunamis, landslides and avalanches. The best known example of an earthquake-induced avalanche is the Huascaran snow, ice and rock avalanche in Peru, in 1970, which buried the towns of Yungay and Ranrahirca. The death toll was tens of thousands of people.

There is some evidence of seismic influence on avalanche releases but this phenomenon is not well understood and even conceptual models are absent. In spite of the high occurrence rate of natural earthquakes over the globe, it is very difficult to plan observational work and obtain comprehensive information about avalanches released by them due to their rarity in any one area. Fortunately artificial earthquakes caused by explosions may be used as an analogue of natural ones. The Khibini Mountains in the Arctic Northwest of Russia is a very suitable area for such studies because they are strongly affected by artificial seismicity caused by explosions in underground mines and open pits of the "Apatit" mining company, and the avalanche period here lasts about eight months a year. Charges of explosions are varied from tens of kilograms to hundreds of tons; the number of explosions is several hundred per winter. Depending on the explosive charge, distance to avalanche prone areas and other factors the explosions can cause very intensive ground shaking comparable with earthquakes of 6–7 rank according to the modified Mercalli intensity scale.

The "Apatit" mining company has a special unit—the Center for Avalanche Safety (CAS)—for avalanche danger prevention and avalanche studies. CAS was founded in 1936 and since that time has accumulated considerable data on released avalanches. These circumstances explain why the Khibini Mountains were chosen for experimental studies of seismic effects on snow stability and avalanche release. The goals of the studies are: 1) To correlate seismic events and avalanche releases; 2) To collect data on ground shaking caused by explosions; 3) To describe snow strength behavior under shaking; 4) To work out models of snow instability appearance and avalanche release. An ultimate goal of the studies is to improve of earthquake or explosion-induced avalanche risk evaluation and working out of rational methods for preventive avalanche release by explosions. The first project was begun jointly by CAS, the Kola Scientific Center of the Russian Academy of Sciences and the University of Bergen in 1999. A comparison of day-of-week distributions of explosions and avalanche releases for two regions—with an open pit mine and underground mine, showed (Mokrov *et al.*, 2000) that they are far from independence (hypothesis of their statistical independence should be rejected at 1% significance level). It is easy to see a shape similarity in the distributions of avalanche releases and explosions (Fig. 1). The correlation between number of days with explosions and avalanche releases is clear enough to be recognized but it is too weak to be used for avalanche prediction. Physically-based models have to be developed and applied for this purpose. To supply the models with data on ground shaking, special seismic measurements were organized together with Murmansk State Technical University. The simulation of seismicity-induced snow instability and avalanche release began simultaneously. The work on creation of a shaking table for laboratory studies of seismic effects on snow strength was started two years ago.

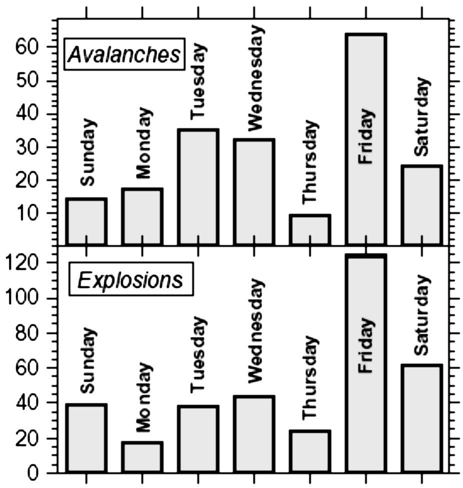

Fig. 1. Number of days with avalanches and mining explosions in the Central mine area. Notice the relatively large number of Friday avalanches, which clearly correlates with the large number of explosions on Fridays that trigger avalanche releases.

2. Seismic measurements

First measurements of 3-component ground accelerations, velocities and displacements were begun at the Nansen seismic station (Chernouss *et al*., 1999), on a mountain plateau in a few kilometres from the explosions. Measurements with portable stations near the explosions (Fig. 2) were begun later. The stationary Nansen seismic station includes three standard Russian seismic sensors CM-3КВ and in the portable station Cossack Ranger (Fig. 3) geophones GS-11D, Geospace Corp., Houston, Texas are used as seismic sensors (Fedorenko *et al*., 2000). It is possible to plug in several 3-component sensors simultane-

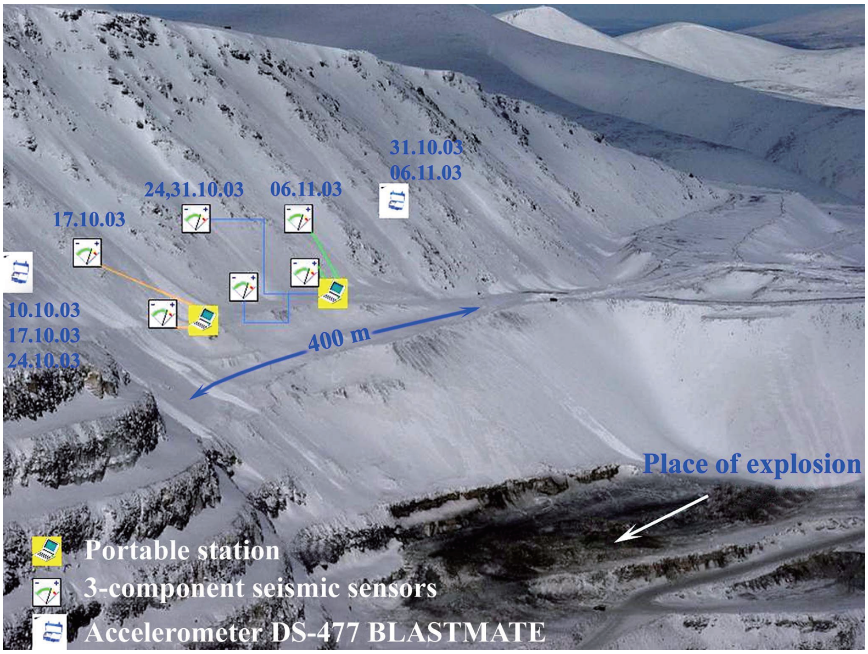

Fig. 2. Avalanche sites, measurement sites and a part of the Central open pit mine with location of explosions.

Fig. 3. Portable seismic station Cossack Ranger.

ously to the portable station. The accelerations at both stations were identical in the range from 0.5 to 40 Hz. For the measurements near the explosion area a standard accelerometer DS-477 (BLASTMATE, Ontario, Canada) also was used. This accelerometer also has a microphone to measure air shock wave pressure.

The measurements showed that the duration of seismic signals caused by explosions depends on the amount of explosive, spatial distribution of charges and type of explosion (aerial or underground), and varies from 2–3 s to 10 s or more. The maximum measured acceleration was 8.7 m/s^2 for the DS-447 and 1.2 m/s^2 for the Cossack Ranger. This difference can be explained by the difference in frequency characteristics of the stations (0.5–100 Hz for the Cossack Ranger and 2–250 Hz for the DS-477). At big distances from explosions, measured accelerations are similar for both stations. In our study we used empirical dependencies of peak ground acceleration $a^{\max}$ (m/s^2) on mass of charge q in kilograms and distance r in meters from the explosion. Such dependencies were obtained by (Kozirev *et al.*, 2000) using the DS-477 separately for open pit mine explosions (1, 2) and underground

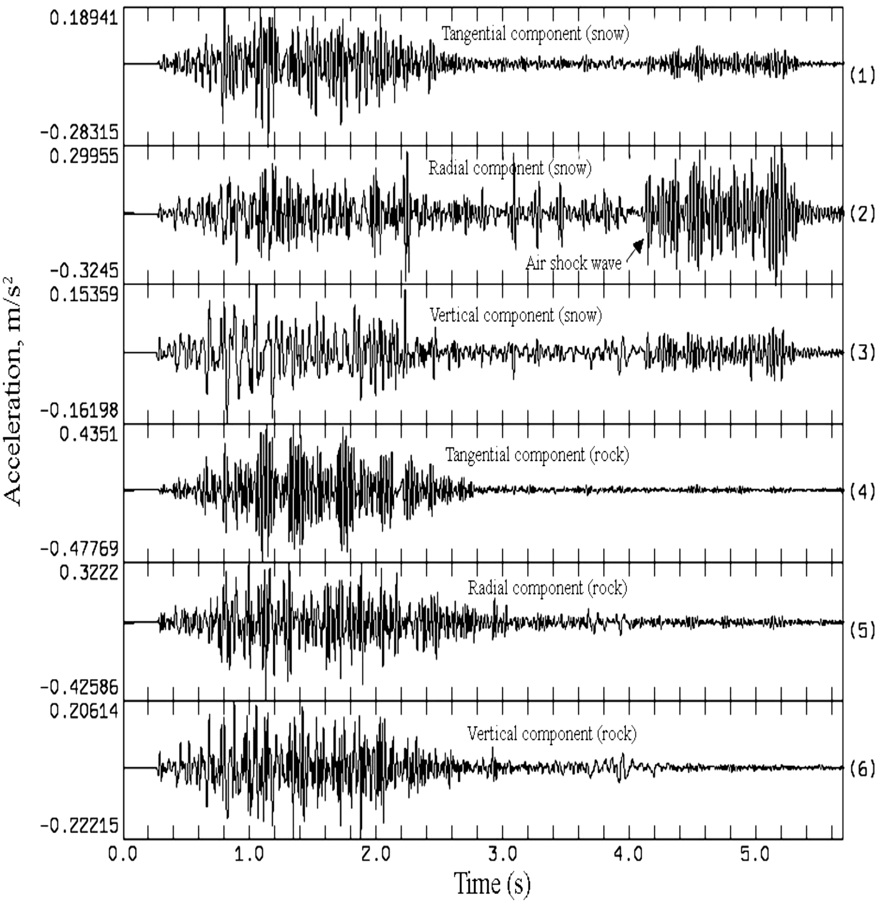

Fig. 4. An example of acceleration records for snow surface and underlying surface (rock). Snow cover depth and mean density at the measurement site are 0.8 m and 260 kg/m^3 respectively.

explosions (3) in the Khibini area. Equation (1) for open pit mines is valid when the parameter $(r/\sqrt{q})$ is in the range [1…5], while eq. (2) is suitable for $(r/\sqrt{q}) \in [5\ldots30]$.

$$a^{\max} = 25.27\,(r/\sqrt{q})^{-1.576}; \quad 1 \leq (r/\sqrt{q}) < 5, \tag{1}$$

$$a^{\max} = 3.64\,(r/\sqrt{q})^{-0.38}; \quad 5 \leq (r/\sqrt{q}) < 30. \tag{2}$$

For underground explosions:

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

High frequency oscillations rapidly attenuate with distance. Oscillations in the 1…5 Hz frequency range may exceed 0.1 g in the vicinity of the explosion zone (within several hundred meters for the Khibinian explosions).

For some seismic events the accelerations were measured simultaneously on rock and snow surfaces (Fig. 4). The measurements showed that at low frequencies the signals are very similar while at high frequencies they are significantly different (Fig. 5). This effect reveals the effective absorption of seismic energy in a thin snow layer at higher frequencies.

Probability density functions of seismic signals (acceleration, velocity and displacement amplitudes) were normal or very close to normal (Fig. 6). This fact is important for mathematical simulation of the seismic influence on snow stability.

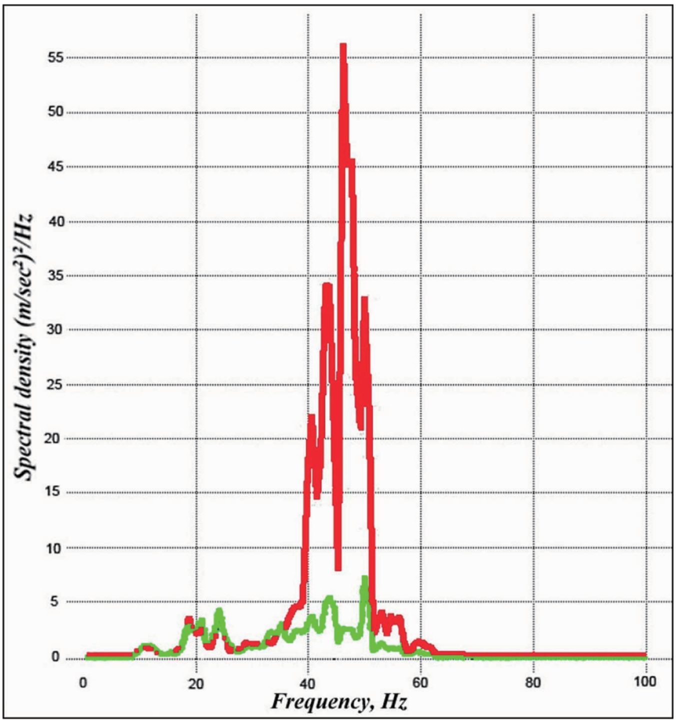

Fig. 5. Spectrum of the radial component of acceleration for the seismic event on 24.10.03. Red line–rock, green line–snow.

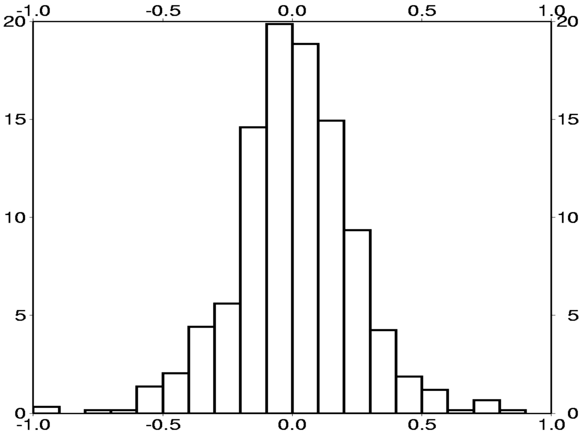

Fig. 6. Histogram of the acceleration normalized by range (in %) for the first three seconds of the seismic event 31.10.03. It is clear that the acceleration p.d.f. is close to Gaussian.

3. Instability simulation

Two approaches for seismicity-induced snow instability and avalanche release simulation were considered—static and dynamic (Chernouss *et al.*, 2002; Fedorenko *et al.*, 2002). In the static approach, taking into account shaking of the underlying surface (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 written as

$$\rho h\,(g\sin\alpha + a_\tau) < c + f\rho h\,(g\cos\alpha - a_n), \tag{4}$$

here: g–the gravity acceleration; a_τ–the tangential component of acceleration directed along the slope (positive acceleration is directed along the slope downward); a_n–the acceleration normal to the slope (positive acceleration is directed normally upward); ρ–snow density; c–shear strength; f–friction coefficient between snow element and underlying surface; h–snow thickness; α–slope inclination. Values of a_n and a_τ depend on distance between the seismic source and (x,y); α also depends on (x,y). The ratio of the sum of friction and cohesion forces to shear forces represents the stability factor F as proposed in (Chernouss *et al.*, 2002; Fedorenko *et al.*, 2002).

$$F(\alpha;\ c,\ f,\ \rho,\ h,\ a_n,\ a_\tau) = \frac{c + f\rho h\,(g\cos\alpha - a_n)}{\rho h\,(g\sin\alpha + a_\tau)}. \tag{5}$$

The snow block is stable if $F > 1$ and unstable if $F \leq 1$. Generally speaking, a_n and a_τ may have different values (even different signs) but in most cases that we observed maximal values of a_n and a_τ were closely correlated and their magnitudes were approximately equal. This makes it possible to use $a_n = a_\tau = a^{max}$ for the least stable case; a^{max} is maximum acceleration for the seismic event and $F(\alpha;\ c,\ f,\ \rho,\ h,\ a_n,\ a_\tau) \approx F(\alpha;\ c,\ f,\ \rho,\ h,\ a^{max})$. This acceleration depends on earthquake magnitude or explosion charge, distance and topography (see eqs. 1–3). Since there is no precise knowledge of parameters constituting the stability factor, these parameters must be considered random variables; exact value of F does not exist. However, it may be worth while to estimate the probability for F to be lower than some threshold F_{thr}, that is:

$$P\{F(x,y) < F_{\text{thr}}\} = \int_0^{F_{\text{thr}}} p_{\text{F}}(x,y;\zeta)\,\mathrm{d}\zeta, \tag{6}$$

where $p_{\text{F}}(x,y;\zeta)$ is a probability density function (p.d.f.) of the stability factor at (x,y). In practice any or all random variables in eq. (5) may be given by their empirical p.d.f.s $p_\rho(\zeta)$, $p_{\text{h}}(\zeta)$, $p_{\text{c}}(\zeta)$ and $p_{\text{a}}(\zeta)$. The only way to obtain p_{F} for arbitrary p_ρ, p_{h}, p_{c} and p_{a} is Monte-Carlo simulation. A similar method was used by Chernouss and Fedorenko (1998) to estimate the spatial distribution of avalanche release probability. This way is computationally intensive but unavoidable, especially if it is necessary to use experimentally

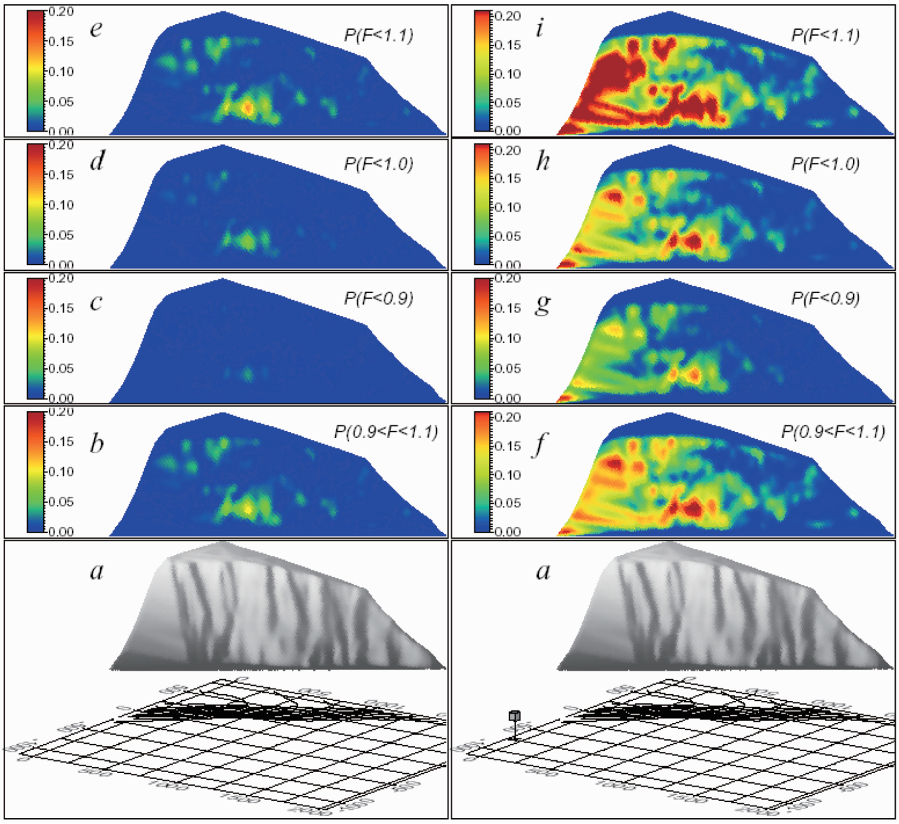

Fig. 7. *The static probabilistic analysis results. The left panel represents the probability distribution of the stability factor without seismic load while the right panel shows the distribution under seismic loading induced by an explosion. Lower frames marked a represent avalanche starting zones in the vicinity of an open pit mine. The location of explosion is shown in the lower right frame by a small cube. Frames b and f show the probabilities of the stability factor F within the interval (0.9–1.1):* $P\{0.9 \leq F(x,y) \leq 1.1\} = \int_{0.9}^{1.1} p_F(x,y;\zeta)\,\mathrm{d}\zeta$. *Other frames show the probabilities of the stability factor for other intervals. Note that the explosion greatly increases the probability of instability.*

obtained probability density functions of ρ, h, c and a which do not belong to theoretical distributions. In Fig. 7 we present our simulation results. We assume that p.d.f.s of random variables $c(x,y)$, $f(x,y)$, $\rho(x,y)$ and $h(x,y)$, belong to normal distributions and these variables are independent. Mean values and standard deviations together with spatial autocorrelation functions were obtained by direct measurements in field experiments. Using this information we create random fields $c_k(x,y)$, $f_k(x,y)$, $\rho_k(x,y)$ and $h_k(x,y)$ for each Monte-Carlo test $k=1\ldots N$ and calculate the random field realization k: $F(\alpha, c_k, f_k, \rho_k, h_k, a^{max})$. Realizations were stored in a file and used later to calculate values of F in each point (x,y) as shown in eq. (6). Results of evaluation of stability factor probabilities can be presented as maps that show stability changing due to seismic effects (see Fig. 7).

As has been mentioned, if $F > 1$ then snow is stable. Real 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 time and an internal slab deformation caused by them is not sufficient for avalanche release. The time span over which these deformations accumulate to a critical value depends naturally both on magnitude and duration of the external loading. One of the ways 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 to underlying rock (Fig. 8) and compares it with a critical value. A critical displacement is used as a criterion of avalanche release in this approach. As was done for the stability factor or its probability, the Newmark displacement can be mapped to reveal places where snow stability is most

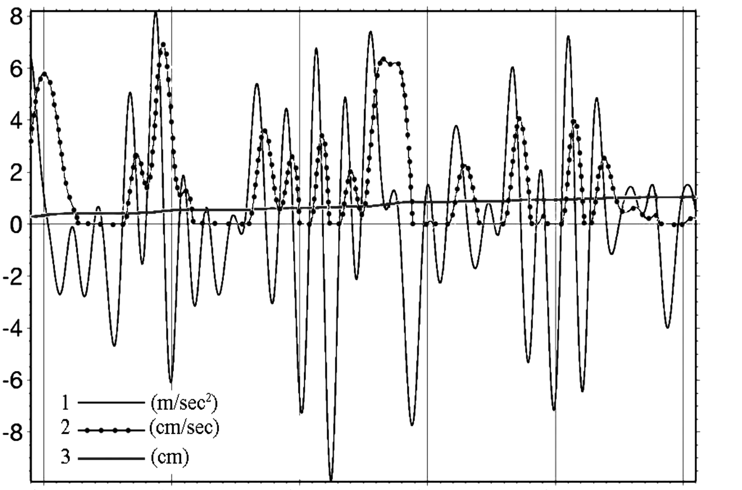

Fig. 8. An example of calculation of Newmark displacement (3). Acceleration measured on the underlying surface (1) and calculated snow slab velocity (2) relative to the underlying surface. The solid line (3) represents relative displacement between snow and the underlying surface. This displacement increases when inertia forces in a snow slab caused by the tangential component of acceleration a_τ exceed forces holding snow on the underlying surface: $a_\tau > c/\rho h + f(g\cos\alpha - a_n) - g\sin\alpha$. According to Newmark, accumulated displacement characterizes stability of the slab; release is improbable if this displacement is small, and very probable otherwise. An avalanche occurrs if this displacement exceeds a value which must be found experimentally.

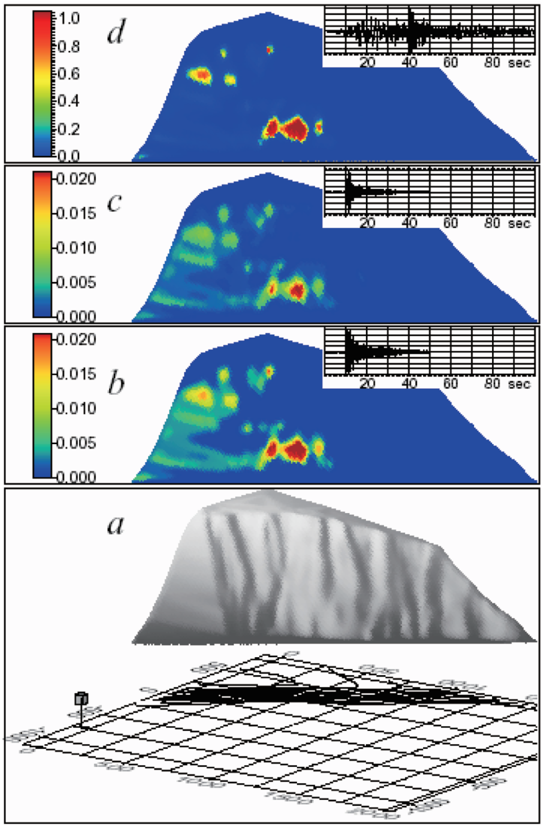

Fig. 9. Application of Newmark analysis to an avalanche prone area. Color bars show displacement in meters. Inserts show seismic time histories used in calculations.

affected by seismicity (Fig. 9). Values of critical Newmark displacement for different types of snow can be obtained from measurements of snow characteristics along fracture lines for seismicity-induced avalanches, or from laboratory experiments. The same approaches as for seismicity can be applied to account for air shock wave influence on snow stability. The essential difference is in that an air shock wave produces only normal loading on the snow pack, which in turn does not produce any snow pack deformation along the slope. Probably other mechanisms of instability exist. For example, both seismic and acoustic effects can collapse an underlying weak layer structure, decreasing shear strength–*c*.

4. Laboratory tests

A review of existing shaking tables showed that they lack the required technical characteristics, are bulky and complicated in mounting and adjustment, are not adaptable for work in field conditions and above all are very expensive. These circumstances forced us to make a shaking table especially for our experiments. Two shaking tables were designed and created to study the instability mechanism, due to snow strength change caused by vibration. The first designed table (Fig. 10) can produce periodic oscillations with frequencies from 1 to 40 Hz and accelerations from 0.001 to 2 m/s^2. Short term damped oscillations were produced by shock loading (Fig. 10). The measuring system for the table was based on that used for the portable seismic station. The software can display shaking parameters such as frequency and acceleration. The table had some disadvantages—it was big and rather heavy (about 50 kg, together with snow sample) and could not produce polarized oscillations. Nevertheless it was possible to do experiments with fresh snow that simulated the effect of snow shear strength decreasing due to shaking of the underlying surface. For example, the experiments with fresh snow carried out under the following conditions: snow

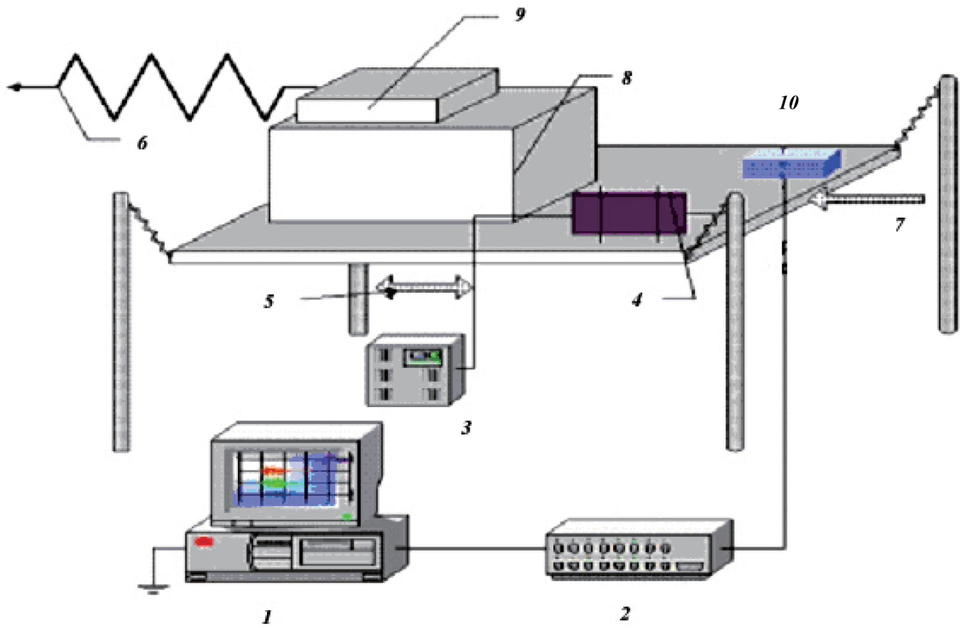

Fig. 10. A sketch of the installation for simulation of seismic vibration and its influence on snow shear strength. 1. Computer; 2. ADC; 3. Frequency regulator; 4. Vibrator; 5. Periodic oscillations; 6. Constant shear load; 7. Short impulse shock load; 8. Snow block; 9. Shear frame; 10. Seismic sensor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

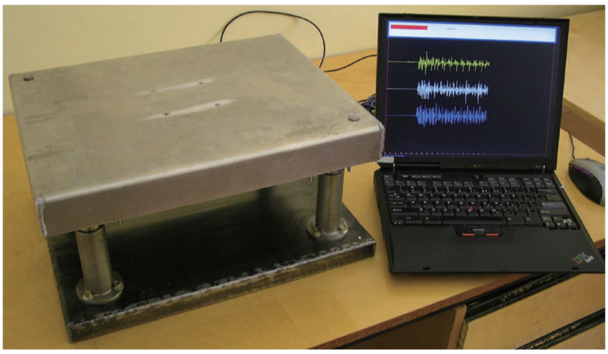

Fig. 11. The modernized shaking table.

density 110 kg/m^3, table vibration 15 Hz, normal pressure on the snow sample 4.9*10^2 Pa, maximum acceleration 0.3 m/s^2, resulted in 3-fold decrease in shear strength practically immediately after the start of shaking. Since the experiments were carried out with natural snow at the CAS field station on the mountain plateau their accuracy was limited, mainly due to spatial variability of shear strength.

A new shaking table was made in 2005. It is more compact (Fig. 11), has the same shaking characteristics as previous one and can produce polarized oscillations to better understand the influence of different types of seismic waves on snow strength. The table is easy transportable and suitable for use with artificial snow in cold chambers to avoid the spatial non-homogeneity peculiar to natural snow.

5. Concluding remarks

The results of our studies clarify the mechanisms of seismicity-induced avalanche releases. It is possible to assess spatial distribution of seismic effects on snow stability and the avalanche release potential. We used empirical equations to assess ground shaking caused by explosions, in case of earthquakes, it is possible to use physically-based numerical modeling for this purpose (Hestholm, 1999).

The studies are continued in several areas. One is to obtain field data and find a relation between snow characteristics and the critical Newmark displacement as a measure of an avalanche release probability. Data is also being accumulated to derive an empirical regression equation estimating the Newmark displacement as a function of shaking intensity and critical acceleration, as Jibson (1993) has done for landslides.

The main attention in the near future will be devoted to an experimental study of seismic effects on snow strength. The studies will be carried out with natural snow and, if possible, also with artificial snow.

The snow instability simulation will be improved by applying the Monte-Carlo method including stochastic simulation of seismic shaking of the underlying surface. Since the parameters controlling snow stability on a mountain slope are spatially distributed, it is convenient to use GIS to simulate the snow instability and avalanche release and visualize the results.

Acknowledgments

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