EXPERIMENTAL STUDY OF SHORT-TERM LOADING INFLUENCE ON SHEAR STRENGTH

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ABSTRACT: It is well known that short-term loadings caused by earthquakes, explosions, skiers etc. can trigger avalanches. There are some models of similar influence on snow stability. One of them ties a loss of snow stability with a possible shear strength decreasing at short-term loading. This work concerns experimental studies of the phenomenon. The experiments were carried out at the Cryospheric Environmental Simulator of the National Research Institute for Earth Science and Disaster Prevention (Japan) and at the field station of the Center for Avalanche Safety of “Apatit” JSC in the Khibini Mountains (Russia). The majority of the experiments were carried out with a specially made shaking table. Shear force and snow sample accelerations were registered with high frequency gages. In some cases shear deformation was also measured. In total more than one hundred experiments have been carried out. It was found that at high rate loading, snow shear strength is significantly less than at low rate ones. Comparison of this effect for different rates of loading and different types of snow has been done. Obtained experimental results and their possible application for snow stability assessment are discussed.

KEYWORDS*:* Snow; Seismicity; Shear strength; Avalanche

1. INTRODUCTION

A coincidence when snow pack with an unstable inner structure is hit by an earthquake can cause catastrophic avalanches. This phenomenon and heavy human losses resulting from this were not only observed in natural environments (such as the mountains of Peru, Russia or Japan) but also at big quarries with strong artificial ground motion caused regularly by technological explosions. For example at the Khibiny mountains (Kola peninsula, Russia) (Fig.1) or at the Taumi-kozan (Itoigawa city, Japan) (Podolskiy et al., 2008a). The forecast of seismic avalanches is in close connection with short-term earthquake predictions. Since both processes are examples of deterministic chaos, and earthquake prediction continues to have no reliable solution (except a 10-30 seconds warning before the appearance of S-waves), we can assess only the probability of avalanche releases during seismic events. For this purpose the change of snow shear strength under vibration must be understood.

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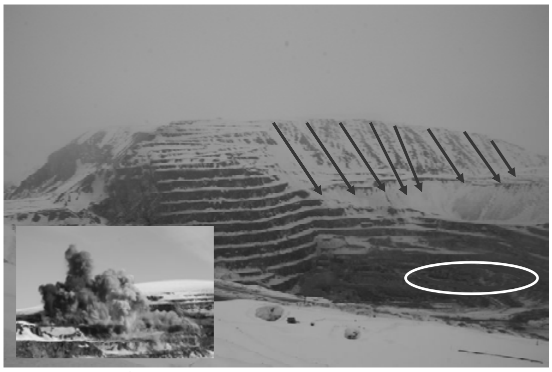

Fig. 1. The *Central* open-cast mine with avalanche sites and location of explosions; weekly technological explosion in the *Rusvumchorr* open-cast mine (200 tons of explosives), *Khibiny* mountains (altitude ~1000 m; 67ºN, 33ºE).

Attempts to evaluate the snowpack stability for examination of seismic effects and avalanche forecast were conducted in the Khibiny Mountains (by Chernous et al., 1999, 2002, 2004, 2006) and some observations and experiments were done in Japan (Higashiura et al., 1979; Ogura et al., 2001; Abe and Nakamura, 2000). However, no information could be found with regards to the seismic effects on the stressed snow supported by detailed and precise measurements, nor with regards to the answer to the question about the physics of the process which causes the fracture of snow. Since the nature of the snow pack response to a strong ground motion is still not well understood, sophisticated study of this is necessary.

Firstly, a joint series of laboratory experiments on the problem of seismic effects on snow stability and avalanches were conducted on the 26-30 of November 2007 and the 10-14 of March 2008 at the Cryospheric Environmental Simulator (CES) at the National Research Institute for Earth Science and Disaster Prevention (NIED, Shinjo Branch), Japan.

This paper presents preliminary results of a comprehensive study of vibration effects on the stability of stressed snow by conducting a number of experiments. Among the latter were tests with different types of stressed snow under polarized vibrations, hi-frequency shear load measurements and hi-speed video filming during the moment a fracture was caused by an impulsive vibration, as well as interaction between different shear rates (slow and impulsive application of the force) and its effects on the snow stability. For experiments with the different shear rates, the use of the new unique method has been proposed (by using liquid as additional shear load; Section 3.5) (Podolskiy et. al., 2008b, Barashev et. al., 2008). The present paper describes the methods, used equipment set-up and obtained results. Next, it identifies the specifics of shear load under impulsive vibration causing fractures. Finally several conclusions are made at the end of the paper.

During the introductory series of experiments (26-30/11/2007) different types of artificial snow (with a variety of snow crystal forms, densities and temperatures) were specially prepared by the CES snowfall facility with its own method. It was possible to observe that any type of snow (wet, granular, fresh, artificially settled, depth hoar) has the same principal respond to vibration: every stressed snow sample had a fracture after an impulsive vibration with any kind of polarization. This was the principal common phenomenon found for every type of snow used. For more detailed observation of the process, a second series of experiments was held (10-14/3/2008) for a selected number of snow types (wet granular and dry granular).

The results clearly show a significant increase of shear load on the snow pack under shaking. There was a twofold increase compared to its static value (i.e. an increase from 0.5 to 1.13 kgf) which lead to a fracture in the snow sample. The results also show much weaker shear strength in comparison with slow shear rate loading. Thus it was possible to suggest that the speed of an applied force to a snow sample could be the most prominent effect of causing snow fracture under vibration.

2. SHEAR FRAME SETTING AND INSTRUMENTATION DESCRIPTION

2.1 Shear frame setting

For shear strength observation the standard shear frame was used during experiments. Despite the fact that more than 25 years ago Perla and Beck (1983) called the shear frame “a useful tool for gathering statistical data on strength distributions ... until a more fundamental technique is developed”, and wrote that “shear frame should be replaced by a device that measures a more fundamental index of the *Gleitschicht* (shear failure plain) this simple *in situ* device is still actively used for avalanche forecasting around the globe and still has no adequate analogs to replace it.

Shear frame and its design was developed and introduced in the 1930s in Russia (Caucasus and Khibiny mountains) (Saatchan, 1936) and later in Europe by Swiss Roch about 1950 (Jamieson and Johnson, 2001). He designed a trapezoidal shape to decrease side friction effects during the pull. This frame also had a pair of intermediate plates which distribute shear stress more homogeneously. For our tests we have used square frames with the area of 0.01 m^2 without fins. This choice was determined by a need to standardize the results (to make results comparable with the tests conducted in Russia according to Russian standards). The frame was constructed from stainless steel. The thickness of metal plates was 0.5 and 1 mm according to the hardness of sampled snow (masses of frames were 0.093 kg and 0.173 kg).

On the 26-30/11/2007, different types of artificial snow were tested. On the 10-14/3/2008, natural granular wet snow, used for the present experiments, was taken from the outside at the plain open surface close to the observation area used by the CES’s staff for systematic snow pit observations (at the place near the CES). Each snow blocks was sampled by the metal basket (removable part of the shaking table) by pushing it slowly into the snow stratum according to the snow stratification chosen for the testing.

Granular wet snow was clearly stratified into a number of layers. Only the upper layer of the snow pit was used for the present tests. It was compounded by rounded grains with a diameter of about 1-1.5 mm (Fig. 2). The upper layer was 7-10 cm thick with a weak horizon of granular snow beneath. This sugar like weak structure was formed by mass consolidations of granules 12-16 mm in diameter. Under it there was an ice crust, 0.5 mm thick. The temperature of the snow was 0.0 - (-0.1)°C; density range was 300-350 kg/m^3. Every time shear frame was slowly inserted into the snow stratum until it reached the upper edge of the second weak layer, which was considered as a potential weak horizon for shear plain. All fractures had a plain surface of these big sintered granules. Outside snow sampling was quite time consuming, on average it took 10 minutes per sample (to cut and bring it into the laboratory). Air temperature inside the cold laboratory was selected according to the outside air temperature and the temperature of snow – 0-2°C.

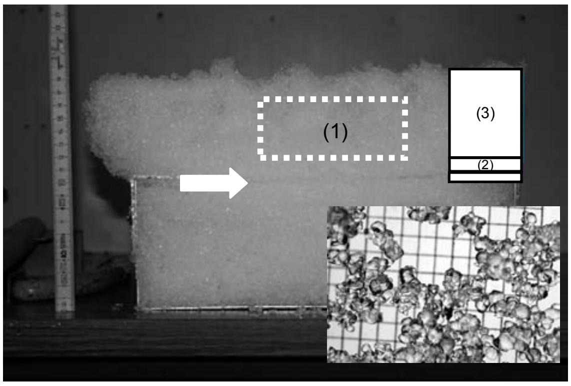

Fig. 2. Metal snow sampler; arrow is showing the ice crust in the middle, which was overlaid by loose snow (2) and used as a shear plane. (1) – indicates where the shear frame has been pushed down; (3) – indicates the upper horizon of the snow profile, used for tests. Rounded grains from the upper snow horizon; 1.5 mm in diameter (cell side is 2 mm).

For the shear strength experiment the shear frame was pushed down into the snow sample as mentioned above. If some sample was too brittle for such an insertion it was precut according to the pattern and thickness of the frame by a snow saw. After this, overflowing snow was removed gently by a trowel to ensure that it does not affect the test by additional friction or mass. Then this was finished, the inextensible metal wire of the load cell was attached to the metal wire between the two sides of the shear frame. The latter was attached to the frame in a way to prevent possible overturning moment. Between the frame-wire and additional load there was the load-cell ("*Kyowa*" with a range 0-50 kgf) for measuring the change of shear load on the snow sample. It was connected to the high frequency electronic recorder by wire ("*Memory HiCoder 8835*").

When everything was set, the frame was either pulled by slowly increasing mass until fracture, or pulled and vibrated until fracture. This pull (and the impulsive vibrations) have produced shear stress concentrations in the snow below every edge of the frame planes, finally resulting in a brittle fracture at the shear plane under the frame. Each fracture was a consequence of different causes, depending on the purpose of the particular test.

The shear load force was continuously recorded through the load-cell by a high frequency electronic recorder with a scan frequency selected accordingly to the aims of experiment (0.5-1 ms). It's peak value at the moment of snow fracture was considered as a maximum shear load force which the snow sample could withstand before a brittle fracture. In most cases the fracture was planar, sometimes with an irregular curve. If it was suspected that the snow sample had a fracture caused during the set-up of the experiment, or if the fracture surface was bigger or deeper than the shear plane under frame, the test's results were rejected. Since all the tests were conducted by one operator (Podolskiy), there should not be any additional variability between tests.

2.2. Shaking table

One of the basic tasks of earthquake engineering is to calculate the loading produced by an earthquake by applying acceleration to the mass of a building, in other words, the inertial force. Despite a number of complexities all dynamic computations are conducted to calculate this inertial force. The inertial force is the value to be estimated to design a structure which would be able to resist such an additional force (Reitherman, 1999). To figure out a similar value experimentally but this time for snow under vibration (the inertial force destabilizing snowpack under stress) 2 kinds of shaking tables were used for observation (only observation obtained from one of these would be discussed here).

The shaking table was brought from the Center of Avalanche Safety, "Apatit", JSC, Russia, to the CES. It was constructed by N. Barashev. Principally its design and use are quite similar to the first shaking tables which appeared in the world for earthquake engineering research (Fig. 3).

The world's first shaking table experiments began in Japan in 1893 by professors F. Omori and J. Milne (Univ. of Tokyo) with the aim of determining the accelerations that had caused the fall of structures. Later F.J. Rogers (Stanford Univ.), interested in the response of soils to strong ground motions, designed the shaking machine (Rogers, 1908). A cart filled with soil was cyclically driven by a DC-powered connecting rod while the recording drum was rotated by hand.

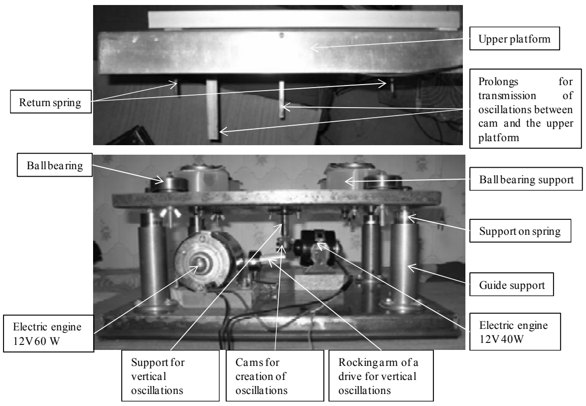

Fig. 3. Photo of the shaking table.

The following type of shaking table for materials study was designed by L. Jacobsen (Stanford Univ.) – it was a steel platform actuated by the impact of a heavy pendulum or by a rotating unbalanced flywheel driven by an electric motor (Jacobsen, 1930).

The method we have used for our studies was quite simple and similar to the one used by Jacobsen in 1930 – he actuated the platform by the impact of the pendulum – in our case it was a pendulum represented by a 1 kg weight hanging on the metal inextensible wire, used for producing the impulsive vibration (Fig. 4).

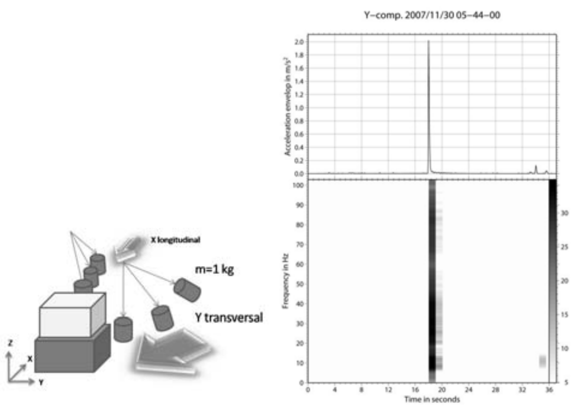

Fig. 4. Diagram of the method used to produce an impulsive vibration by the pendulum and an example of an acceleration envelope (m/s^2), and frequency records.

There is no need to mention that strong ground motion produced by earthquakes or explosions is much more complex than any single impulsive or harmonic oscillation. Only simple damped oscillations were used in experiments. However, by considering diverse earthquakes, it is possible to find the wave forms that are similar to simple impulsive vibration (refer to Fig. 12 at Kanamori, 2004).

2.3. Acceleration and displacement recording and processing

Along with the change of the shear load (Fig. 5), accelerations at the metal basement of the snow block and displacement of the shear frame were recorded. Three components of acceleration (x, y, z) of the shaking table were continuously recorded with a frequency of 514 Hz by using the device designed at the Polar Geophysical Institute, Kola Science Center, Russian Academy of Science (Analog-to-Digital Converter -"*ADC*"). This was installed under the metal basket for the snow block. All accelerograms were created with the PC program *Cossac Ranger II* and processed and represented graphically with *Adobe Photoshop 6.0* software (Fig. 4).

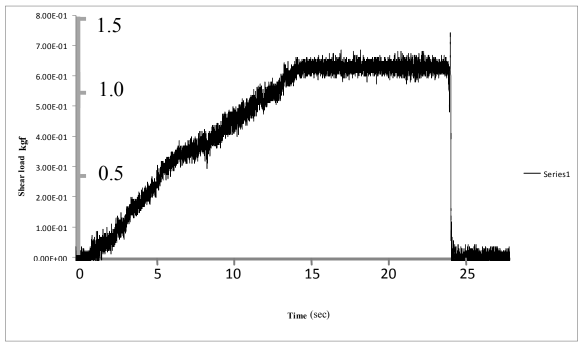

Fig. 5. Typical record of shear load change and a fracture after an impact (fresh pressed snow, ρ = 120.6 kg/m^3).

For some cases the displacement of the frame was continuously recorded by a laser rangefinder installed on a tripod near to the snow sample. The aim was to observe how the metal frame was moving before and during an impact, produced from two different directions (Fig. 6).

Records of shear load and displacement, created by high frequency electronic recorder ("*Memory HiCoder 8835*") were simply records of voltage saved as usual *.txt files and calibrated and processed later with the *Microsoft Office Excel 2007*.

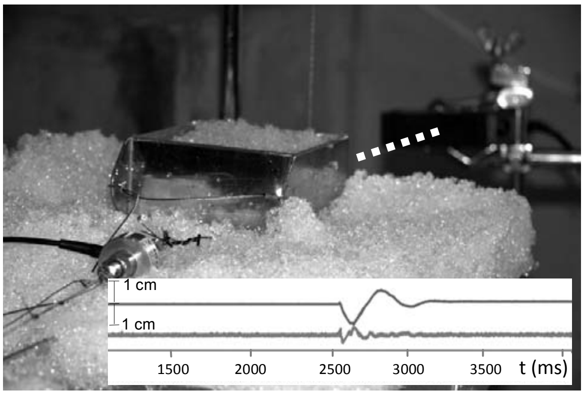

Fig. 6. Laser rangefinder in front the shear frame and an example of a shear load and laser rangefinder signals record (a case without fracture after an impact; with a 0.8 kgf loading on the snow before the impact. Upper line is a laser rangefinder signal (cm), lower line is a shear load change (kgf).

3. HI-FREQUENCY SHEAR LOAD RECORDING DURING A FRACTURE CAUSED BY AN IMPACT

Most tests on the 12th of March were recorded with a high frequency sampling rate equal to 500 μs (max memory limit was 25 s). The use of such hi-resolution was due to a need to get insight into the changes of shear load occurring at the moment of an impact unseen with a normal sampling rate (1 ms). By doing so it was possible to figure out the specific pattern of the shear load curve typical for the moment of snow fracture.

The first series of tests were done without any additional vibration and recorded at normal sampling rate (1 ms). Shear strength of snow was tested in a specific method, by pulling the frame slowly with an additional mass: after connecting the load cell to the shear frame from one side and to a load on the other, the load (1-3 kg) has been slowly released and pulled the frame with some particular shear force rate – this created a stress on the snow and a fracture resulted. This critical shear load value was almost the same for a number of tests with this particular type of snow and was considered as a maximum shear load (~47 sec, 3.0 kgf).

The following series of tests was recorded with a high sampling rate (0.5 ms) and was conducted in the same manner as described above, but with a lighter load than the critical mass. This meant that a smaller mass was hanging freely on the wire and there was no fracture, since the shear stress was not enough to cause the break in the snow. This made the snow sample's condition very close to unstable with very low stability factor. If this mass was left hanging on the sample it would not fall for many hours (Barashev et. al., 2008), but if external force was added – e.g. an impulsive vibration (with any polarization) - produced by a light impact ($a_{max\text{-}aver.}$= 1.47 m/s^2) to the metal basement of the sample – snow always momentary collapsed (additional load = 0.54-1.14 kgf, difference between normal long-term loading and sum of static and dynamic loadings during an impact = 0.86-1.5 kgf). To clarify further the moment of a fracture, this hi-frequency sampling rate was used.

Presented here is the typical shear load curves during an impact and the consequent fracture recorded at the sampling rate – 500 μs. All graphs look principally the same (Fig. 7): a small peak at first, then – U-form decrease and increase of the shear load, a second higher peak and fracture at this moment. Note the steep increase of shear load before the second peak: the force (<1.88 kgf) has been applied within a very short period (<53.5 ms). Only the "down slope" part after the second peak on every graph differs. This part is represented by a number of "jumps" resembling a "footstep" and determined by a heterogeneous manner of the shear frame glissade after the fracture – caused by dynamic resistance during the ploughing of granular surfaces. The causes of the fracture are discussed in the following section.

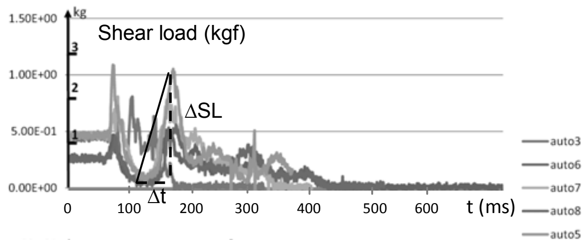

Fig. 7. Hi-frequency shear load records during an impact, plotted on one graph. The curves are overlaid with the point of an impact acting as the start.

4. INTERACTION BETWEEN SLOW SHEAR RATE AND VIBRATION, AND THEIR RESULTING EFFECTS ON THE SHEAR STRENGTH OF SNOW

A special approach was developed and proposed to test snow samples for shear strength with different shear rates and their interaction with an impulsive load, produced by an impact (presented by short term impulsive vibration). For this purpose a special technique proposed by Chernous (Podolskiy et. al., 2008b) was developed to control the shear rate without resorting to expensive sophisticated equipment.

The shear rate was controlled by a uniform stream of liquid through a tube, pouring into a plastic container, attached to the shear frame (Fig. 8).

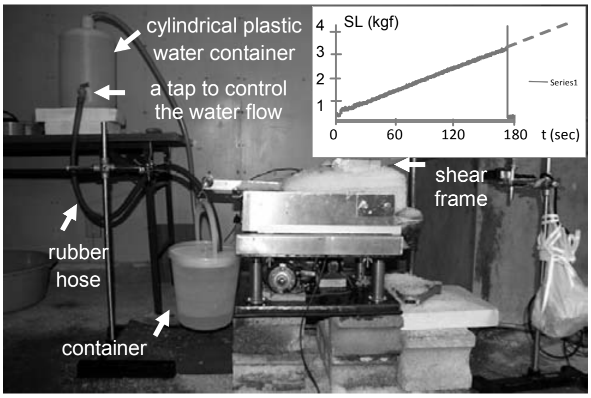

Fig. 8. Method of experiment with controlled shear rate. Typical record of the shear load change for particular shear rate with a peak, corresponding to an impact and following fracture. Dashed line is an extrapolation which shows the shear load change without any impulsive vibration before natural fracture occurs.

There were a big cylindrical container filled with water, and a tap to control the water flow, a rubber hose to direct this water into the container hanging on the inextensible metal wire which was attached to the shear frame.

Two types of snow were used (wet snow from outside (ρ=320 kg/m^3, t=-0.0°C, Fig. 2) and cold granular natural snow formed by equitemperature metamorphism and stored at the cold room (ρ=170 kg/m^3, t=-15°C). For the latter the air temperature in the cold laboratory, where the test took place, was set at -10°C.

Snow sample was loaded gradually by filling the plastic container with water, which was attached by wire to the frame with the load cell in-between. Shear rate was controlled by fixing the water flow speed at a particular value by the position of the tap. During tests – the shear load, the displacement (by laser rangefinder) and time before the fracture were recorded. By choosing different shear rates it was possible to obtain Fig. 9. We could thus confirm the fact that shear strength of snow is much stronger if the force is applied slowly, and found that the shear rate interval and the absolute value of the shear strength has not changed after some time (after 3 min it did not change as dramatically as it did when the mass was applied faster within 0-2 min. Fractures could thus happen at a very low mass if shear rate was fast). Measured varieties of shear load values for the same snow for different shear rates was about 500% (if the force was applied fast (within 1 s) the absolute value of the critical shear load was ~1 kgf; if the shear force has been applied slowly (within 5 min) - the critical shear load was ~5 kgf).

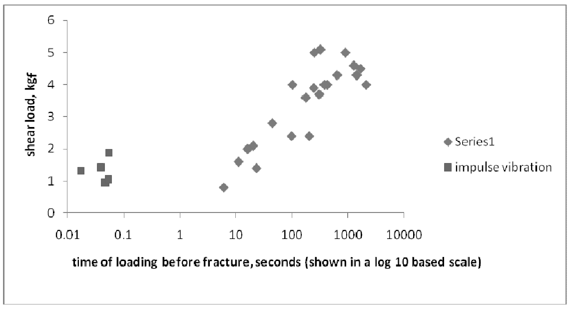

Fig. 9. Time before fracture within which the shear load force (absolute value) has been applied for normal shear frame test with different shear rates (series1, plotted with ♦ dots) and time of shear loading before fracture for impulsive vibration (plotted with ■ dots).

The following objective was to observe the interaction of slow shear rate loading and fast shear rate loading (impulsive) on the snow sample at the same time. The same shear rate was set and used for all tests during the day. On average it took 4-5 minutes with the chosen shear rate to produce a fracture in the snow sample (~4.9 kgf). But if we had added a slight impulsive vibration (produced by an impact to the basement of the metal container containing the snow sample, additional load ~0.76 kgf) before this critical value, we got a fracture at a much lower value of shear load (1.6-3.0 kgf; 3 times lower (Fig. 10)). That has suggested that short term impulsive effect on snow produced by some external factor like explosion or earthquake can make stressed snow much weaker (thus more prone to collapse).

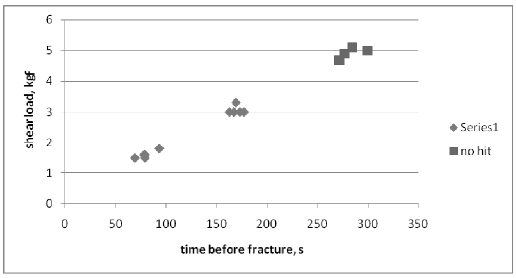

Fig. 10. The shear load and time before fracture for wet granular snow. Shear rate was the same for all sets of results. Normal snow fracture indicated by ■ dots. Fracture caused by an impulsive vibration (additional load 0.5-1.5 kgf) indicated by ♦ dots.

In case of slow shear rates, wet snow sample was deformed to 5 mm on average when the fracture occurred, after crossing this threshold it has collapsed. Dry snow deformed only by 1.0-0.5 mm. However, when we used vibration – snow stratum had no time to redistribute inner stresses between granules by slow deformation and melting, and collapsed just at the moment of impulsive vibration, due to critical concentrations of increased strain between snow grains. Due to the impulsive vibration, the force (ΔSL~1kgf) causing the fracture was applied within an extremely short time interval (~46 ms) (Fig. 9).

5. HI-SPEED VIDEO RECORDING DURING A FRACTURE CAUSED BY AN IMPACT

A hi-speed camera was used to determine the precise moment when the snow fracture occurs. The frequency of the camera was selected as 200 Hz. For this observation a number of tests were filmed from both sides of the experiment's working place (x and y-axes) and from above (z) by constructing a special stage for the hi-speed camera.

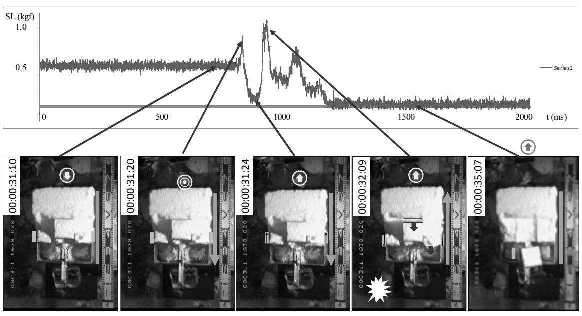

Fig. 11. Frames from the hi-speed video record showing the moment of snow sample fracture under an impulsive vibration. Long arrows are indicating the moments corresponding to the shear load changes at the hi-frequency record. The circle is indicating the pendulum; the short bands are showing free laying small snow pieces, the long band shows the displacement of the shaking table.

These videos have shown that the snow fracture occurs not at once with the impact (by x or y-axes), but during the resonating wave (when the platform is about to backtrack to the initial state before an impact) when the inertia reaches its maximum (Fig. 11).

An interesting observation was that snow debris, laying freely on the tested snow sample (left after the frame set and cutting; i.e. – without shear strength, just friction), flies away from the sample at the same moment that the snow fracture happens.

6. CONCLUSIONS

The following conclusions can be made based on the present study: Even a slight impulsive vibration could destabilize stressed snow of any type. The applied force depends on the value of long-term and short-term loadings (produced by vibration), but even the sum of these (for the moment of a fracture) is always smaller than the long-term static value of critical shear load. Shear strength under short-term loading is much weaker in comparison with slow shear rate loading and it was possible to suggest that the speed of an applied force to a snow sample could be the prominent factor causing snow fracture under vibration.

Shear force has a different nature if it has been applied to a snowpack by long-term loading (for example produced by snowfall or wind-loading) or by short-term loading (caused by earthquakes, explosions, cornice collapses, skiers etc.). The short-term loading causing the snow fracture can be few times smaller in comparison with the long-term loading. For some types of snow values for long-term or short-term loadings can be different for an order of magnitude (Barashev et. al., 2008). Since the snowpack, laying on the slope, accumulates very slow (agreeably, shear force grows under very slow shear rate) field shear frame tests should be conducted with as minimally low shear rate as possible (1-3 min instead of standard 1-10 sec practice). Short-term shear frame tests cause the underestimation of the snow shear strength in comparison with the real natural conditions. The practice would show how applicable this method is; but at least, the values of stability indexes would characterize the snow stability more precisely. For shear frame tests related to the short-term loadings it is expedient to use the values equivalent to long-term loading. The latter ones could be obtained in the course of further experiments with the different types of snow. Future study is also necessary to understand the seismic influence on the stability of snowpack and investigate how this influence can be incorporated into avalanche forecast.

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