FIELD EXPERIMENTS ON WEAK LAYER FAILURE AND CRACK PROPAGATION DUE TO EXPLOSIONS

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ABSTRACT: Avalanche control by explosives is among the key temporary preventive measures and fixed avalanche control installations are frequently installed today. Hitherto, little is known about weak layer failure and crack propagation due to an explosion. In the winter 2013-2014 we performed field experiments on a flat study site. We triggered slurry explosive charges ranging from 4.25 to 5 kg as used in avalanche control at different heights above the snow surface. At three different distances from the point of explosion we measured surface air pressure and accelerations within the snowpack at various depths. Cameras were placed in the snow pits for recording weak layer failure and crack propagation and to monitor the snowpack deformation by particle tracking velocimetry. We assessed whether weak layer failure occurred and if so whether it was caused by crack propagation or the direct impact of the air pressure wave above the point of observation (pit). We compared these results to the data recorded by the accelerometers and microphones to obtain magnitudes required to cause weak layer failure in a given snowpack. First results show loading conditions using explosives required to fail a weak layer given a certain snowpack.

KEYWORDS: avalanche control, avalanche formation, weak layer failure, crack propagation

1. INTRODUCTION

Avalanche control by explosives is among the key temporary measures and fixed avalanche control installations are frequently installed and successfully used today. Pressure waves originating at the point of detonation propagate through the air and are partly transferred into the snowpack. The latter propagate through the ice lattice and the pore space and are supposed to cause weak layers to fail so that an avalanche releases.

In order to assess whether an explosion had an effect on snowpack stability, one has to know whether a possible weak layer has failed. As weak layer failure is associated with collapse (e.g. van Herwijnen et al., 2010), failure can be determined by evaluating vertical snowpack displacement. Snowpack deformation caused by explosions can either be measured by sensors buried in the snowpack (Bones et al., 2012; Gubler, 1977; Simioni and Schweizer, 2013) or by particle tracking velocimetry (PTV) using video cameras (van Herwijnen et al., 2010). These methods usually require a snow pit for device installation but allow for high frequency real-time measurement of the dynamic deformation. A penetration profile acquired with a high resolution snow micro-penetrometer (SMP) would allow for semi non-destructive measurements (Schneebeli and Johnson, 1998), but only just before and after the explosion. Assuming a linear-elastic constitutive behavior of the snowpack, compressional stresses can easily be calculated (Kolsky, 1953) as previously shown by Gubler (1977).

Displacement can either be caused by weak layer failure leading to collapse or snow compaction due to the impact of the explosion. Acceleration sensors and particle tracking velocimetry are restricted to certain points within the snowpack or at the pit wall, respectively. However, whether weak layer failure occurred or not, can simply be determined by visual inspection of the PTV camera images.

The aim of this study was to compare accelerometer data and PTV images during explosions. Furthermore, it was intended to qualitatively assess weak layer failure. From these results loading conditions required to fail a weak layer given a certain snowpack when using explosives were estimated.

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2. METHODS

2.1 Study site

The military firing range in Hinterrhein (Switzerland) was used for the experiments. It is characterized by various plane level study sites at an elevation of 1680 m a.s.l. with a rather uniform snowpack.

Snow depth at the nearby snow observation station of Splügen was above average for the period of the experiments in winter 2013-2014. Snow depth at the study plot reached 180 cm on the test day investigated.

2.2 Explosive charges, triggering

An explosive charge usually used in fixed avalanche control installations in Switzerland was employed for these experiments. The slurry explosive charges, ranging from 4.25 to 5 kg were put directly on the snow surface or fixed to a pole elevated between 1 and 3 m above the snow surface to achieve best effectiveness (Gubler, 1976; Johnson et al., 1994). The charges were triggered by electronic detonators.

2.3 Measuring equipment

In order to install the measuring equipment, snow pits (usually 3) were dug at different distances from the point of explosion.

Accelerometers were installed by introducing them from the pit wall at different distances from ground zero and at different depths into the snowpack. Microphones were placed at the snow surface to measure the air pressure resulting from the explosion. Data acquisition was automatically triggered at the time of the explosion.

Cameras manufactured by GoPro were placed inside the snow pits and used in high speed mode to record the pit wall which was equipped with markers. This allowed for recording the displacement within the snowpack.

A manual profile was taken in one of the snow pits. Density was measured in each snow pit using a capacitive sensor (Denoth, 1989).

2.4 Failure initiation

One can discriminate between weak layer failure due to crack propagation and due to the direct impact of the air pressure wave at the location of observation due to different wave propagation velocities and a resulting time delay. Crack propagation happens at much lower speed than propagation of the air pressure wave through the atmosphere with subsequent propagation through the snowpack to the weak layer (Birkeland and van Herwijnen, 2012; Gubler, 1977; Simioni and Schweizer, 2013).

2.5 Failure mechanism and identification

The air pressure resulting from an explosion hits the snowpack with a positive and a negative pulse which lead to corresponding loading of the snowpack. During the positive compressive pulse, a weak layer will fail if the compressive strength or rather the shear strength are exceeded (Simioni et al., 2014). The negative peak stresses will be lower than the positive maximum stresses and in most cases not cause failure.

Assessing the video stills of an experiment allowed to identify whether there had happened weak layer failure or not.

2.6 Deformation and loading

Accelerations were directly measured by the installed accelerometers. Displacement velocities and displacements were derived by integration. Air pressure was measured with the installed microphones at the snow surface.

Stresses were calculated assuming a linear elastic material behavior. This is a strong simplification of the complex wave propagation behavior in snow which would be described most accurately by Biot's theory (Johnson, 1982). We measured density ρ at different depths within the snowpack. We derived the wave propagation velocity c_p inside the snowpack based on the wave arrival times at two vertically separated sensors in a pit. The elastic modulus E can then be obtained:

$$E = c_p{}^2 \rho \, .$$

Normal stresses were calculated using the relation

$$\sigma = \frac{v_{\text{disp}}}{c_p} E$$

where v_{disp} is the displacement velocity (Kolsky, 1953).

3. RESULTS AND DISCUSSION

We performed 37 experiments during the winter 2013-2014. In the following, we mainly present the exemplary results of one experiment (25 February 2014). However, the qualitative observations we report have been observed in several experiments.

3.1 Weak layer failure

Snow depth in the study area was considerably above average and contributed to good snowpack stability without persistent weak layers (Schweizer and Wiesinger, 2001). Nevertheless, weak layer failure could be recorded at distances close to the explosion and in near-surface layers, especially with new snow conditions.

During the negative impulse of the wave, weak layers and the above snowpack were lifted if failure happened in layers close to the surface and at observation points close to the explosion, e.g. below the new snow. This allowed for clear identification of failure. If failure happened in deeper snowpack layers, the failure could usually still be identified due to the sudden displacement of the snowpack above the weak layer.

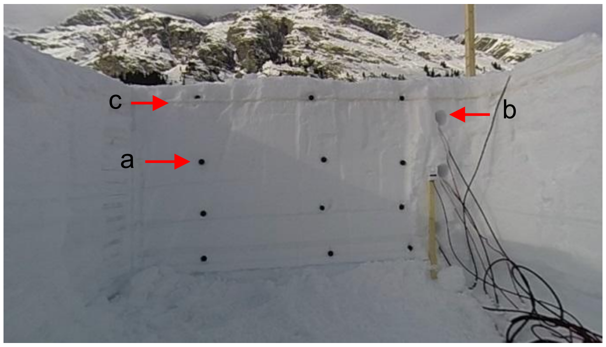

Fig. 1: Snow pit wall with a) markers, b) holes for accelerometers, c) weak layer (failure). The snowpack above the weak layer c) was lifted due to the negative pressure impulse.

Although loading was higher due to larger charges and measuring closer to the point of explosion compared to the preceding season (Simioni and Schweizer, 2013), no crack propagation through the weak layer triggered close to the detonation point could be observed during the experiments. Crack propagation was likely not observed since the snowpack was stable and no prominent weak layer was present. Failure mainly happened below the uppermost layer consisting of new snow or decomposed and fragmented precipitation particles.

In order to release an avalanche, slab and weak layer must be prone to crack propagation (Reuter et al., 2013). Crack initiation is expected to occur close to the detonation point where the impact is largest. If near the detonation point no suitable slab and weak layer combination exists so that crack propagation cannot occur, a running crack may still be initiated further from the detonation point where the snowpack is more prone to propagation. In that case it is important to know whether the impact of the air pressure wave at the point of observation is still large enough to cause weak layer failure and subsequent crack propagation.

3.2 Air pressure

Air pressure at the investigated pit showed the distinct shape of a blast wave, with a positive peak pressure of 17.5 kPa and a negative peak of -5.34 kPa at a distance of 12 m from the point of explosion.

3.3 Accelerations

The accelerations reached 135 m/s^2 at the uppermost accelerometer. These values decreased significantly with depth down to 28 m/s^2 for the lowest sensor around 80 cm below the snow surface. The vertical acceleration at the depth of the failed weak layer was derived by extrapolation of the lower sensors and reached 270 m/s^2.

3.4 Stresses

The elastic modulus, calculated with measured densities and propagation velocities, was in the range of 60 to 90 MPa, i.e. high – as expected for an estimate derived from a highly dynamic loading experiment.

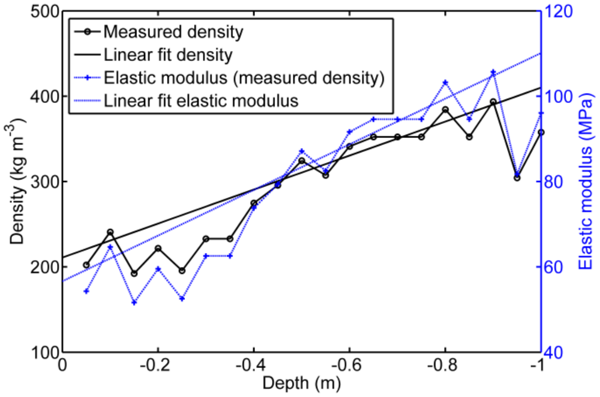

Fig. 2: Density and corresponding elastic modulus vs snow depth. The green line indicates linear fit to density.

In our experiment, the weak layer failure occurred approximately 12 cm below the snow surface. The uppermost accelerometer was buried 19 cm below the surface. The peak normal stress at 19 cm was ~8.8 kPa. This value is rather low compared to typical values of compressive strength but above tensile strength of snow (Shapiro et al., 1997). Slightly higher, at the depth of the weak layer, the compressive stresses were probably larger. However, as shear stresses could not be determined, it is not possible to say whether the respective strength was exceeded. Deeper in the snowpack, layers generally have higher density and higher strength, if there are no persistent weak layers, and the stresses calculated in these layers were low and hence likely insufficient to cause failure. However, other experiments with larger charges, in closer distance to the point of explosion and/or different elevation of the charge did cause failure of layers deeper in the snowpack.

So far we could not calculate the shear stresses since we were unable to determine the shear waves and their amplitudes in the accelerometer signal as the measurements were performed very close to the detonation point and the shear wave was not delayed sufficiently so that the different wave modes could be separated.

4. SUMMARY

We performed experiments to assess the impact of an explosion on the snowpack. We measured air pressure, accelerations and monitored the snow pit wall with cameras to detect failure and derive loads required to fail a weak layer.

We detected failure below a layer of recently fallen snow by evaluating the camera stills. For the single experiment analysed here, we observed that the surface layer was lifted up – indicating failure between the surface layer and the underlying snowpack. Normal compressive stress was about 9 kPa, i.e. within the order of magnitude of compressive strength. Close to the surface, the compressive stresses were in the order of magnitude of the surface air pressures.

In the next winter, we will perform experiments again if possible under more unstable snowpack conditions, and plan to compare the effect of different kinds of explosions.

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