FIELD MEASUREMENTS AND MODELING OF WAVE INDUCED WEAK LAYER FAILURE DUE TO AN EXPLOSION

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ABSTRACT: Little is known about the mechanisms involved when triggering avalanches artificially by explosions. Here we test the hypothesis that weak layer failure is mainly initiated by wave induced stresses exceeding the strength of the specific layer. We therefore performed experiments with explosives on a flat study site in winter 2013-2014 in wet and dry snowpacks. At three different distances from the point of explosion we measured surface air pressure and accelerations within the snowpack at various depths. We evaluated snow density and dielectric properties with conventional methods in snow profiles and used this information together with empirical relationships to build a Biot-type porous model of the snowpack. Acoustic wave propagation was simulated by solving Biot's equations numerically with a pseudo-spectral approach. Failure in the snowpack was modelled if compressional and shear stresses exceeded the strength limits for the corresponding snow density. Modelled failure locations were compared to the actual appearance of fractures in the field measurements. The results are a promising step towards models including more complex geometries which will help to improve planning of fixed avalanche control installations.

KEYWORDS: avalanche release, avalanche control, wave propagation in snow, numerical modeling

1. INTRODUCTION

Fixed avalanche control installations have gained popularity during the past years primarily to protect infrastructure. For an informed decision on where to locate installations in the release zone to have adequate coverage and hence to reduce the residual risk to a target level, it is desirable to know how far away from an explosion a weak layer is still likely to fail.

Since the pioneering work by Gubler (1977), flat field experiments on avalanche control have been performed by Ueland (1993) who focused on far distances, and Bones et al. (2012) who studied the effect of an explosion on the snowpack near the point of detonation. Gubler (1976), Johnson et al. (1994) and Mellor (1973) found that best effectiveness was obtained for an explosion a certain height above the snowpack. Small scale experiments were performed by Johnson et al. (1992) and revealed the principle behavior of snow under dynamic loading. Johnson (1990) developed a simple model to predict shock wave attenuation in snow, focusing on short distances from the explosion. Biot's theory, which describes wave propagation in porous media, had previously been applied on snow by Johnson (1982). A finite element model for rapid loading was developed by Haehnel and Shoop (2004). Miller et al. (2011) developed a numerical model to study the response of snow to explosions. Recently, a pseudo-spectral model for porous materials solving Biot's equations with a pseudo-spectral approach was developed (Sidler et al., 2010).

The aim of this study was to explore whether weak layer failure initiated by wave induced stresses can be adequately modeled. We compared results of field experiments to numerical simulations based on a Biot-type porous model of the snowpack. The stress field of the simulation was evaluated based on the failure criterion to obtain the locations where snowpack failure had occurred; those were then compared to the failure locations found in the field experiments.

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2. METHODS

2.1 *Field experiments*

The field experiments were performed on a plane, level study site at an elevation of 1680 m a.s.l. (Simioni and Schweizer, 2013). The experiments during the preceding winter showed a very uniform snowpack (Simioni and Schweizer, 2013).

During winter 2013-2014, snow depth at a nearby observation station was well above the average. Snow depth at the study site reached 180 cm during this season. A manual profile including snow density measurements with a capacitance probe (Denoth, 1989) was observed on the day of the experiments and indicated good stability (Schweizer and Wiesinger, 2001).

For the explosive source we chose Alpinit, a slurry explosive widely employed in avalanche control installations in Switzerland (Simioni and Schweizer, 2013).

Charges ranging from 4.25 to 5 kg were fixed to a pole at elevations of 2 and 3 m above the snow surface. The charges were triggered with electric detonators.

Measuring equipment was placed in three snow pits at different distances from the detonation point. Acceleration sensors were buried in two of the snow pits at different depths. Microphones were installed above all three snow pits to measure the resulting pressure in the air above the snowpack. All measurement installations were automatically triggered at the exact time of explosion. Cameras manufactured by GoPro were installed in all snow pits to visually identify the failure of weak layers.

2.2 Numerical modeling of wave propagation

A poroelastic model of wave propagation is much better suited to describe wave propagation in snow than the conventional elastic or viscoelastic models commonly applied in seismology (Johnson, 1982). To this end we solved Biot's (1962) equations of motion with a pseudo-spectral approach which is known to be accurate and efficient (Sidler et al., 2010). We also consider the wave propagation in the air above the snowpack and in the ground below the snow.

Compressive and shear strength were parameterized depending on snow density (Jamieson and Johnston, 2001; Shapiro et al., 1997). Failure occurs if the modeled stresses exceed the strength at a given point within the snowpack.

A Friedlander wavelet was used to model the pressure source with parameters based on the field measurements of air pressure (Fig. 2).

3. RESULTS

3.1 Acceleration

The accelerations of the snowpack showed a clear attenuation with depth and distance from the blast. Acceleration for three different depths at a distance of 27 m from the source can be seen in Fig. 1.

The typical waveform consists of a first dominant sharp pressure wave followed and superposed by pressure and shear waves with smaller amplitudes arriving at the sensor. This corresponds well with a Friedlander source waveform that is often associated with explosive sources in air. The corresponding waveform and frequency content are shown in Fig. 2.

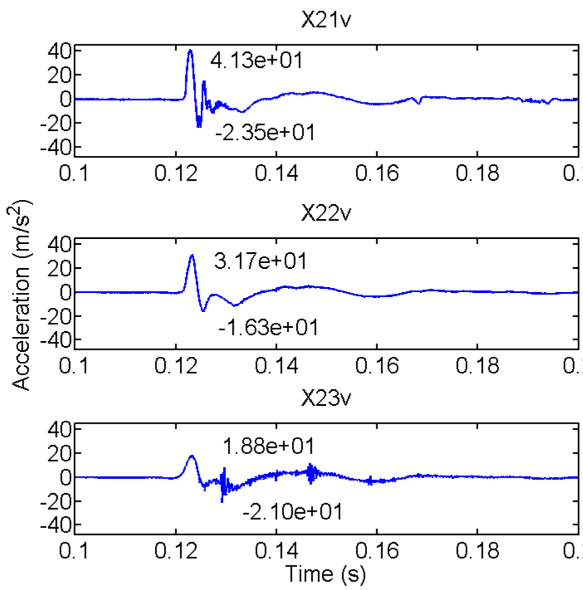

Fig. 1: Vertical accelerations for sensors at a distance of 27 m from the point of explosion and three different depths (21, 50 and 78 cm below the snow surface).

3.2 Air pressure

As the air pressure wave propagates from the point of detonation it is subject to geometrical spreading and interference with reflected and transmitted wave modes. The measured air pressure for the modeled experiment decreased exponentially from ~17 kPa at a distance of ~12 m from the blast to 4 kPa at 22 m. The attenuation of the air pressure wave amplitude in the field experiments varied between $x^{-1.5}$ and $x^{-2.5}$, where x is the distance from the point of explosion.

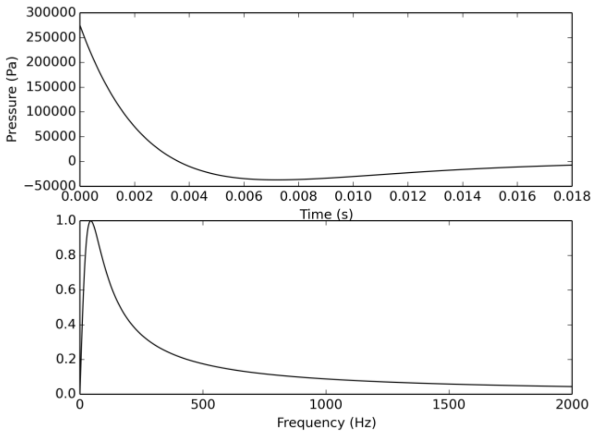

Fig. 2: Waveform and frequency content of the Friedlander wavelet used as pressure source in the simulation. The source is located in the acoustic layer above the poroelastic snow layer.

3.3 *Weak layer failure*

The stills from the videos recorded in the snow pits during explosion revealed that weak layer failure mainly occurred below the top layer consisting of new snow and partly decomposed and fragmented precipitation particles. We attribute the absence of failure in deeper layers to the stable structure of the snowpack; persistent weak layers were not present.

3.4 *Model*

We simulated the propagation of an acoustic wave by 2D wave propagation on a 1D snowpack model

Fig. 3: Porosity model for the numerical modeling. The snowpack is a one-dimensional model based on measured density and is displayed in different shades of red. Gray indicates air and a water saturated sandy subsurface below the snowpack is shown in blue color. The model is 19 m long and snow depth is 175 cm.

based on the density profile observed in the snow pit. We simulated the air above the snowpack as a purely acoustic medium supporting only one pressure wave mode and used the appropriate open pore boundary conditions at the air-snow interface. For the ground underlying the snowpack we used the properties of unconsolidated, water-saturated sand with considerably higher wave velocities. The model for porosity is shown in Fig. 3.

3.5 *Simulation*

During the time of the simulation snapshots of the stress fields are written out in short time intervals and evaluated for maximal stress conditions that the snowpack can withstand. We therefore distinguished between deviatoric (shear) and axial (bulk) stress fields. The corresponding stress fields 2.7 milliseconds after the start of the simulation are shown in Figures 4 and 5, respectively. The model suggests that the snowpack mainly failed in shear near the uppermost layers of the snowpack. Due to the considerably higher wave velocities of the sand underlying the snowpack the waves were strongly transmitted into the ground and the sand layer behaved almost like an absorbing boundary.

Fig. 4: Snapshot after 2.7 ms showing the pressure in the air above the snowpack, the deviatoric (shear) stress in the subsurface (blue for positive stresses) and the locations where the maximum shear stress exceeded the strength (in red) during the time of the simulation.

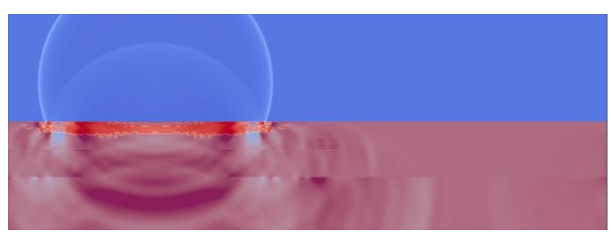

Fig. 5: Same as Figure 4 but uniaxial (bulk) stress (ruby for negative stresses) is shown instead of deviatoric stress and locations where strength is exceeded (luminous red).

4. SUMMARY

We performed field experiments with explosives and recorded air pressure, snowpack acceleration, stratigraphy and density. We used density and air pressure measurements as input for a Biot-type porous representation of the snowpack. We then solved Biot's equations with a pseudo-spectral approach and compared the locations of the stress field exceeding the maximum strength of the snowpack to the locations where snowpack failure was identified in the field experiments.

The modeled air pressure was in good agreement with the values measured in the field experiments, considering the error of a 2D model compared to the spherical expansion of the wave in the experiment. Defining the correct shape and values of the input wavelet including amplitude and frequency content based on the air pressure measurements is crucial to obtain a modeled snowpack response similar to the measured response. Although using smaller charges, the air pressures modeled by Miller et al. (2011) were higher than those modeled here but nevertheless in the same order of magnitude. A shear stress concentration was observed above the weak layer as detected in the explicit model used by Miller et al. (2011).

The model suggests that weak layer failure occurs mainly due to shear loading in the uppermost part of the snowpack as observed from the camera stills.

In the future, we will refine the model with data from more field experiments and compare the results to those that can be obtained with the explicit model developed by Miller et al. (2011).

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