COMPARING TWO METHODS OF ARTIFICIAL AVALANCHE TRIGGERING: GAS VS. SOLID EXPLOSIVES

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ABSTRACT: Remote avalanche control systems (RACS) are increasingly employed to protect transportation routes. The surcharge on the snowpack, which may lead to failure and subsequently to an avalanche, is caused by an explosion, often by igniting a gas mixture or solid explosives. With both types of explosions avalanches can efficiently be triggered – as numerous systems are successfully operated around the world. However, it is not clear how much the two methods differ with regard to their impact on the snowpack – apart from the obvious fact that the tube-like systems used for gas explosions cause a directed impact. We performed side-by-side experiments on a flat field with a prototype gas exploder and solid explosives. By testing both methods on the same day at the same location we tried to avoid the influence of snow properties on the impact characteristics. Our results show that differences in the air pressure above the snow surface as well as the accelerations within the snowpack are relatively small between the two types of explosions for a similar energy density – at least in the direction of the gas exploder axis. Both quantities strongly decay with increasing distance from the point of explosion. At large distances, say 100 m, the impact is small with both methods and the additional load caused on the snowpack seems insufficient in most cases to trigger an avalanche. Hence, we confirm that both types of explosions are efficient, but avalanche triggering seems rather be caused by initiating a crack close to the system where the impact is large, with subsequent crack propagation across the slope.

KEYWORDS: snow cover, snow avalanche control, artificial triggering, explosion, air pressure wave

1. INTRODUCTION

The preventive triggering of avalanches by igniting either solid explosives or a gas mixture is the most popular avalanche control method. The local surcharge caused by the explosion is supposed to cause the failure of a snowpack weakness with subsequent crack propagation and slab release. The aim of artificial triggering is to control starting zones that endanger infrastructure – typically ski runs or transportation corridors. By triggering an avalanche, the risk can be reduced and closing times can be kept to a minimum – often only the time needed for the control operation, rather than waiting for the natural stabilization of the snowpack. Moreover, frequent “cleaning” of starting zones may prevent the accumulation of a thick slab potentially resulting in a large or very large avalanche and also mitigate a potential wet-snow problem in spring. If a control operation is not successful, i.e. no avalanche could be released, the snowpack has still been “tested” and a natural avalanche is unlikely provided the shot placement was appropriate and conditions are not changing. Various delivery methods exist with hand charging, “helicopter bombing” and fixed installations being the most popular ones. In particular the latter method, also called remote avalanche control systems (RACS), is increasingly employed. Thousands of systems have been installed over the last two decades and operate successfully in mountain ranges around the world. Still, the relative efficiency of the various methods is unknown as comprehensive comparative tests are missing.

Some of the principles of the effect of explosions on snow were described in the pioneering works of Mellor (1965; 1973) and Gubler (1977). Some more recent studies include Binger and Miller (2016); Miller et al. (2011); Suriñach et al. (2011); Tichota et al. (2010); a comprehensive literature review is provided by Simioni (2017). Recently, Simioni et al. (2015) performed a series of measurements to determine the effects of solid explosives on and within the snowpack, but also studied the directed impact caused by a tube-like gas exploder (Simioni et al., 2017). These two most recent studies clearly show the considerable decrease of the impact with increasing distance from the point of explosion but also with depth within the snowpack. However, no direct comparison of the two triggering methods (solid explosives vs. gas) was provided.

Our aim was therefore to perform side-by-side experiments to determine the impact of a directed gas explosion as well as of an explosion by igniting solid explosives. The comparative

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experiments should provide insight into the relative efficiency of the methods commonly employed in RACS.

2. METHODS

Experiments were performed during three days (16-18 February 2016) on a military firing range near Hinterrhein (Switzerland); Simioni et al. (2015) describe the study site in detail. Snow depth at the level study site was about 60 to 70 cm. The snowpack was spatially rather uniform; the snow was dry, but warm (-1 °C) with an approx. snow density of 285 kg m^{-3}.

The measurement setup was similar to the one described by Binger and Miller (2016). At three distances (varying between 13 and 49 m) from the point of explosion the air pressure close to the snow surface (3 to 5 cm) was measured with microphones. At the same time, the accelerations were measured within the snowpack in two different depths (varying between 11 and 54 cm from the snow surface). Data were recorded at a sampling frequency of 20 kHz. In the case of the gas explosion, which causes a directed (not radially symmetric) impact, we measured along two axes to assess the lateral decrease of the impact. Microphones could at least resolve frequencies up to 1 kHz, which was sufficient for our setup as we did not measure within a few meters of the point of explosion.

We used commonly used powder explosives in RACS (Riomon T1), which were triggered electrically with a blasting machine. Charge size varied between 2.4 and 4.8 kg. Charges were mounted above the snow surface (in most cases elevated by 2 m) on a wooden stick.

A mobile prototype gas exploder, provided by TAS, the manufacturer of the Gazex® system, was used to perform the gas explosion experiments. The gas exploder consisted of a steel tube open on one side (length: 2.5 m, inner diameter: 80 cm); it was suspended from a crane and anchored to the ground with steel wires and concrete blocks to absorb the recoil. The angle between the exploder axis and the snow surface was 30 to 36°, similar to operational systems. The two gases (oxygen and propane) were stored in tanks at a pressure of 6.5 and 1.4 bar, respectively. The gas then flowed for a certain period of time from the tanks into the gas exploder where it mixed. A plastic lid prevented the gas from flowing out of the tube before the explosion. This was required since the oxygen-propane mixture is heavier than the ambient air. The gas mixture was ignited using spark plugs. The quantities of the gas mixture varied between 0.5 and 1.9 kg.

The methods are described in more detail in Simioni et al. (2015) and Simioni et al. (2017).

3. RESULTS AND DISCUSSION

We analyzed 22 experiments with the prototype gas exploder and 9 with solid explosives, which were all performed during three days in February 2016. This allows for a direct comparison independent of external influences.

Figure 1 shows two examples of the air pressure signal for gas and solid explosives. In both cases, the typical wave form showed a sharp pressure increase at the beginning followed by a drop, with a longer phase of negative pressure (underpressure). All measurements are compiled in Figure 2 for air pressure and in Figure 3 for air pressure increase per time. The air pressure strongly decreases with increasing distance from the point of explosion. The decrease of p_{max} can be described with a power-law relation $p_{max} = 10^{a} x'^{b}$, where x' is the distance scaled with either the gas or explosive mass; a and b are constants. In case of the experiments with solid explosives the exponent was found to be

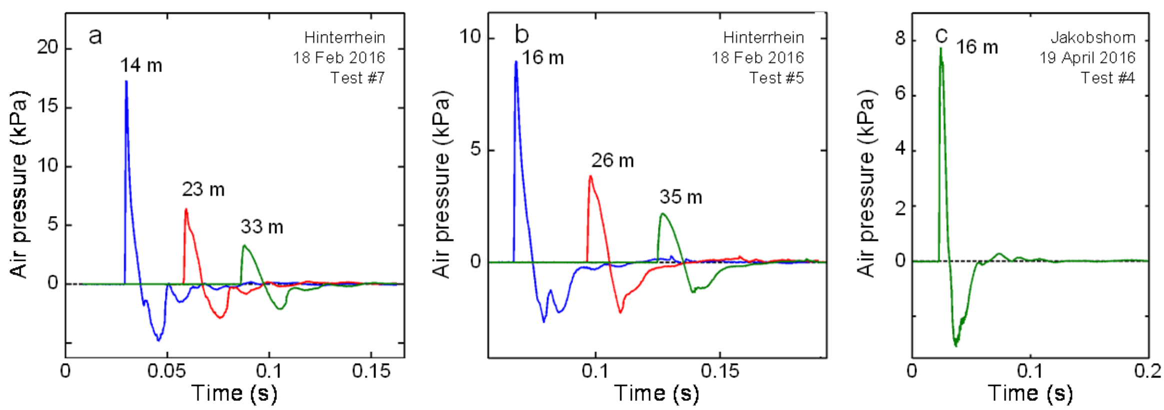

Figure 1: Examples of air pressure signals for (a) solid explosives (4.8 kg Riomon), (b) experimental gas exploder (1.7 kg gas mixture), (c) operational Gazex (1.5 m^3).

about -1.9, whereas it was about -1.7 for the experiments with the experimental gas exploder. These values of the exponent b agree well with the previously reported values by Simioni et al. (2015; b = -1.7) for solid explosives and Simioni et al. (2017; b = -1.7) for gas. Similar values between -1.1 and -1.9 were reported in other studies (Simioni, 2017; see Table 4.5).

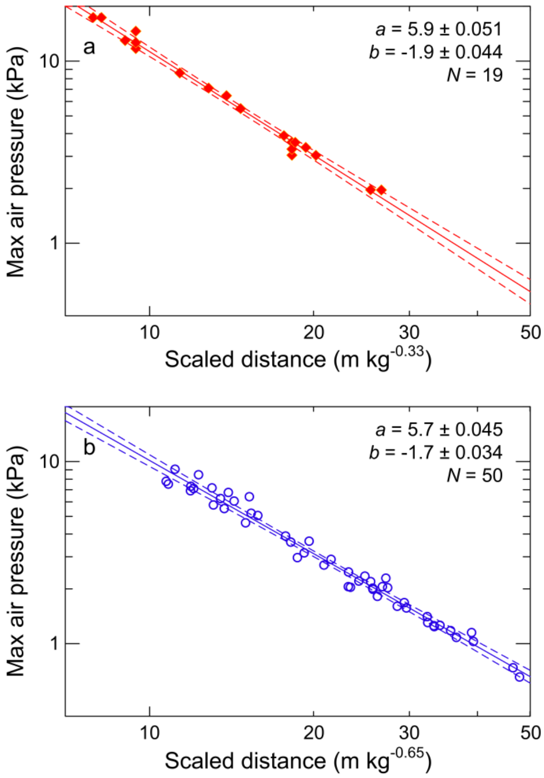

Figure 2: Maximum air pressure near the snow surface for experiments with (a) solid explosvies and (b) gas.

The main frequencies in the air pressure signal were between about 20 and 40 Hz for both types of explosions. A clear decay of the energy with distance was observed, but the main frequencies did not change. The signals were hardly composed of frequencies above 500 Hz. Above 500-800 Hz the energy content was very low. The pressure peaks were well reproducible indicating that the measurement setup for the distances where we measured was appropriate.

Due to the fact that the mass scaling differs between solid explosives and gas, the scaled distances cannot directly be compared. However, if we assume a charge of 4.8 kg solid explosives and a gas mass of 1.9 kg, we can compare at which distance the air pressure is the same. For a given air pressure of, for instance, 1 kPa the distance is about 61 $\pm$ 2 m for the solid explosives and about 59 $\pm$ 2 m for the gas. Hence, the values are similar. In general, the air pressure was slightly higher for the solid explosives, in particular for lower distances (<40 m). On the other hand, if we extrapolate the air pressure at a distance of, for instance, 100 m, we can expect an air pressure between 320 and 480 Pa for the solid explosives, and 330 to 510 Pa for the gas. These values of the additional air pressure at the snow surface seem too low to cause a weak layer failure within the snowpack where the impact is strongly attenuated. In the case of the experimental gas exploder, these values can be expected along the gas exploder axis and within a forward cone of half angle of about 37°. At larger angles from the exploder axis, the impact is lower. However, the directed impact, which is not spherically symmetrical as in the case of solid explosives, becomes less prominent with increasing distance from the point of explosion.

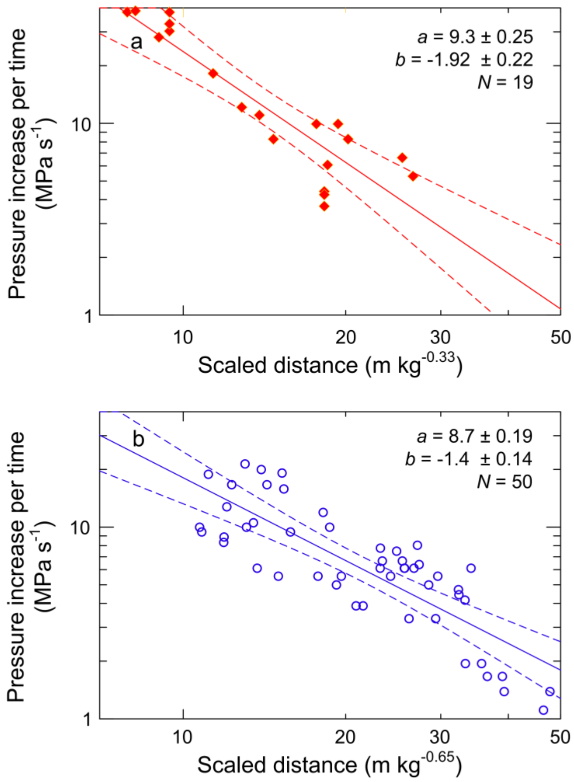

Figure 3: Maximum initial increase of the air pressure per time $(dp/dt)_{max}$ for experiments with (a) solid explosives and (b) gas.

The initial increase of the pressure was large, near the point of explosion (~15 m) about 10-30 MPa s^{-1} corresponding to a very strong impact, which can likely cause a failure in a weak layer (Figure 3). Overall the increase was similar, but initially slightly stronger for the solid explosives compared to the results obtained with the experimental gas exploder. In both cases, the air pressure derivative strongly decreased with increasing distance. Nevertheless, at a distance of about 80 m, the increase was still about 1 MPa s^{-1}.

For both types of explosions, the impact within the snowpack, i.e. measurements of acceleration, strongly decreased with increasing depth as has been shown by Simioni et al. (2015) and Simioni et al. (2017).

Figure 1c shows an air pressure signal of an operational gas exploder (Gazex®, 1.5 m^3) located at the Jakobshorn (Davos, Switzerland). The comparison with the pressure signal from the experimental gas exploder suggests that results obtained with the experimental gas exploder can be considered as representative of the impact caused by operational exploders.

4. CONCLUSIONS

We performed side-by-side field experiments with solid explosives and an experimental gas exploder. Results suggest that with both types of explosions the impact near the point of explosion (<40 m) is very large and will likely cause weak layer failure. Absolute values obtained with solid explosives are slightly larger, but overall can be considered as similar given the experimental uncertainty. Moreover, in case of the experimental gas exploder, the results are rather lower estimates for the indicated gas masses.

In any case, the results obtained with the experimental gas exploder cannot directly be related to operational gas exploders. Nevertheless, comparative measurements at an operational gas exploder showed that the air pressure signal of the experimental gas exploder was very similar to the one of the operational exploder suggesting that the results of the experimental gas exploder are rather representative.

Given the relatively low values of the air pressure at distances larger than about 60 m suggests that triggering of dry-snow slab avalanches by the air pressure impact at the snow surface far from the point of explosion is rather unlikely. Whereas we do not contest that occasionally avalanches were triggered at these large distances, we suggest that in most cases when avalanche width is large, the wide fracturing is likely due to extensive crack propagation in the weak layer – with crack initiation near the point of detonation (Simioni and Schweizer, 2013). Hence, the concept of the so-called effective radius should be critically revisited in view of new experimental results and the improved understanding of dry-snow slab avalanche release.

Finally, it has to be pointed out that the pressure impact is only one of many criteria that need to be considered when planning remote avalanche control systems.

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