Avalanche triggering by sound: myth and truth

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ABSTRACT: It remains a popular myth that avalanches can be triggered by noise. We will take a closer look and compare the impact of sound, the supersonic boom caused by low flying military aircrafts and explosives on the snow cover. Avalanche release by explosives is the method of choice for avalanche mitigation and for achieving infrastructure safety by avalanche control services. Explosions lead to high pressures and acceleration rates. Wave propagation is possible in three media: in air, within the snow cover and through the ground. Depending on the type of source, shock or pressure waves originate and propagate in air. Having reached the air-filled pores in the snow the latter may affect the ice matrix. The deformation caused is assumed to be proportional to the pressure amplitude of the wave at the surface. The pressure amplitudes caused by shouting or loud noise are at least about two orders of magnitude smaller (a few Pascal) than known efficient triggers. Triggering by sound can therefore be ruled out as a triggering option.

KEYWORDS: snow avalanche, avalanche release, explosive control

1 INTRODUCTION

Most dry-snow slab avalanches release naturally during or shortly after storms. They are caused by slow, but uniform external perturbations such as snow accumulation. Avalanches can also be triggered by localized rapid perturbations (near surface dynamic loading). These external perturbations are commonly caused by over-snow travellers (skiers etc.) or explosives. Occasionally avalanches have been triggered by earthquakes (LaChapelle, 1968), low flying military aircrafts (sonic boom) and approaching or landing helicopters. Triggering by sound, e.g. shouting or another loud noise, is mentioned as a triggering option in some books (Flaig, 1935; Spilsbury and Spilsbury, 2003) and seems to remain a popular myth (Tremper, 2001). Though, Tremper (2001) explicitly discards this triggering option and Barton and Wright (2000) call corresponding reports apocryphal. Whereas triggering by skiers, snowboarders and snowmobiles or snow cats is well researched (Föhn, 1987), similarly so for explosive control (Gubler, 1977), the evidence for triggering by aircrafts is sparse (Perroud and Lecomte, 1979) and inexistent – to our knowledge – for triggering by sound.

The aim of this study is to compare the effect of various triggering sources, in particular explosives, sonic boom and sound, and evaluate whether triggering by sound is possible or can be ruled out based on order of magnitude estimates.

2 FORCES AT THE SNOW SURFACE

Initial failure in a weak layer below the slab (which may propagate and eventually lead to slab release) can be due to an additional force at the snow surface. The shorter is the impact, the more likely failure is since snow strength decreases with loading rate. Various sources of loading exist – surely of extremely varying intensity:

- the sound emitted by a person shouting at the bottom of a slope resulting in an acoustic pressure wave
- the acoustic pressure wave due to an approaching helicopter
- the pressure applied on the snowpack due to the static load by a skier
- shock and acoustic pressure waves from aircrafts with velocities $v > c_{\mathrm{air}}$ (with c_{air} the speed of sound in air, about 340 m/s)
- shock and acoustic pressure waves caused by detonations above the snow surface.

With the exception of the forces exerted by a skier (commonly modelled as a surface load on an elastic half space causing elastic stress), the other sources are all related to the pressure of sound waves propagating through the air. Therefore, we focus on the description of sound waves and their propagation.

3 WAVES AND WAVE PROPAGATION

Any source of sound will produce pressure waves in air. Sound waves in air are longitudinal waves which arise from the alternate compression and expansion of the air in rapid enough manner to be an adiabatic process (Davis, 2000, p. 29).

Assuming that sound waves are small amplitude disturbances of a body of compressible

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gas, the one-dimensional equation of momentum conservation for a plane wave in the x-direction can be written as (Billingham and King, 2000, p.41)

$$\rho \frac{\partial \tilde{u}}{\partial t} + \rho \tilde{u} \frac{\partial \tilde{u}}{\partial x} = -\frac{\partial \tilde{p}}{\partial x} + \frac{\partial^2 \tilde{u}}{\partial x^2} - \rho g$$

with ρ the gas density, p the gas pressure, u the gas velocity g the gravitational acceleration and t time. Gravity is assumed to act in x-direction, and the symbol $\tilde{}$ indicates fluctuations.

The two terms on the left hand side are the acceleration terms; the second term describes nonlinear convective accelerations. It can only be neglected if velocity fluctuations are smaller than the speed of sound, i.e. for small Mach numbers. On the right hand side the pressure gradient force, the viscosity term and the gravitational force appear. To neglect the viscosity term we must confine to frequencies well below 10^9 Hz. In order to neglect the third term on the right hand side we must require frequencies f higher than 10^{-2} Hz.

In the case of normal (linear) acoustic waves – audible sounds roughly lie in the range 20 Hz < f < 2×10^4 Hz – we can neglect the three terms discussed above. Although we are dealing with finite amplitudes, for example pressure amplitudes that are small compared to the atmospheric pressure, we have to take into consideration that first high pressures, cause higher temperatures and higher propagation velocities. Therefore the wave crests of the pressure waves will move faster than the troughs. Second, the pressure amplitude can rise to magnitudes of several atmospheres but cannot decline below zero.

In the limit case of propagation velocities in the range of the speed of sound, however, we will have to deal with nonlinear convective accelerations, especially when we consider waves with large amplitudes, i.e. shock waves as caused by explosions (Billingham and King, p. 41).

To produce shock waves either a large amplitude disturbance, such as a detonation, or a small amplitude disturbance which lasts for a long time is needed. Supersonic aircrafts can be taken as an example for the second case (Billingham and King, 2000, pp. 246, 252).

For shock waves we can still assume an inviscid gas and neglect gravity effects. The conservation of mass, momentum and energy lead to the Rankine-Hugoniot relations (Billingham and King, 2000, p. 243). Their interpretation is that on the front side of the shock waves the flow is subsonic, whereas behind them it is supersonic. Pressure, temperature, density and velocity change abruptly. For a shock wave propagating from left to right pressure and temperature are higher on the left while the density will decline just after the shock wave has passed. The velocity decreases from left to right with a supersonic discontinuity at the wave front.

Shortly after initiation of a single shock, the wave can be described as an N-shaped pressure wave (N-wave) with amplitudes smaller than the atmospheric pressure. From several experiments measuring the attenuation of the N-wave in air it arises that the distance from the source where just N-waves are observed is well below 10 m (Gubler, 1977). Eventually, the N-wave will attenuate to a normal acoustic wave (small-amplitude wave).

Sommerfeld (1982) stated that the assumption of two ways of wave propagation in the material snow seems reasonable. Disturbances (waves in air) initiate (i) different kinds of displacement waves (longitudinal, transversal and surface waves) within the snow cover (and the ground), and (ii) also propagate through the pore gas (air pores in the snow).

4 WAVE PROPAGATION IN AIR

A point source emitting one single disturbance causes a pressure wave in air, which travels by definition at the speed of sound. Its intensity is attenuated due to spherical spreading of the wave fronts. The waves' intensity will be dissipated by reasons of losses in thermal conduction: during times of high pressure higher amounts of thermal energy are emitted than can be gathered during phases of low pressure (Bergmann, p. 548). Attenuation is proportional to $1/r^2$ where r is the distance from the source. Dissipation can be described with an exponential decrease:

$$I \propto I_0 \frac{e^{-ar}}{r^2}$$

with a dissipation constant a. For frequencies f < 1 kHz dissipation will be smaller than 2 ppt and negligible. Acoustic waves travelling through air mainly suffer losses due to attenuation.

For example, a loud scream produces a pressure amplitude $\hat{p}$ = 2 Pa. The intensity of a acoustic pressure wave is related to its pressure amplitude

$$I_0 = \frac{1}{2\rho_{air} c_{air}} \hat{p}^2 .$$

Standard values yield $I_0 = 5 \times 10^{-3}$ W/m². In a distance of 10 m, the intensity decreases to $I_0 = 5 \times 10^{-5}$ W/m², i.e. I_0 is two orders of magnitude smaller, but still well within the audible range.

Shock waves emitted continuously by a source over long time can travel several hundreds of meters. Aircrafts at supersonic speeds produce pressure jumps with amplitudes of a few 100 Pa within tens of seconds near the ground. The common temperature profile gives rise to the attenuation of energy of the shock waves propagating from higher to lower levels in the atmosphere, because the speed of sound increases with the path travelled downwards. Furthermore, the overpressure can overshoot the mentioned values if the aircraft's path is bent and shock waves converge in a focal curve on the ground (Bergmann, pp. 540, 546).

5 WAVE PROPAGATION IN SNOW

From an energy source above the snow surface one sort of waves will directly enter into the snowpack, another will travel through the air above and affect the snowpack in farther distance. We will consider the latter for wave energy dissipation is smaller in air.

When a pressure wave meets the snow surface it couples with a different medium. The impedance matching ratios, given as the products of densities and velocities of sound of the two media, are not equal, but are rather unfavourable for wave energy transmission between the media air and snow (Mellor, 1965). Having entered the snowpack the N-wave penetrates into the pore system and causes stresses in the ice skeleton (Gubler, 1993).

The displacement caused within the snowpack by the pressure wave travelling above the snow surface is roughly proportional to the pressure amplitude of the disturbance (Gubler, 1993). The additional stress in the snowpack can be estimated from measured displacement speeds. A displacement speed of 10 mm/s corresponds to a stress of about 1000 Pa.

Snow is a very efficient absorber of shock wave energy. The Hugoniot characteristics show the behaviour of a certain medium for the variables pressure and density. Snow has a narrow span of elastic behaviour that changes to plastic behaviour with declining specific volume. Being highly compressible over a wide range from 2 to 12 MPa snow will efficiently absorb shock waves originating close to the snow cover (Mellor, 1965). The radius of permanent deformation (crater zone) is relatively small – only about 1 m for a 1 kg charge.

6 PRESSURE ESTIMATES

In the following we will compare the intensities of explosives, aircrafts and the human voice by regarding the maximum pressure amplitudes. The pressure amplitude squared is proportional to the intensity, if the density ρ_{air} and the speed of sound c_{air} are assumed constant (Table 1).

6.1 Explosives

As shock waves are absorbed quickly, it is the pressure wave which is relevant for affecting the ice skeleton.

According to Gubler (1977) explosives are best placed 1 to 2 m above the surface to affect the snowpack effectively. The radius of an explosive's impact follows the relation: $r \propto r_0\ W^{0.5}$, with r_0 the radius of impact of a 1 kg hand charge and W the charge mass. Doubling the impact radius requires a charge four times heavier. The attenuation of the pressure wave and the associated impact area of detonations have been determined for various conditions by Mellor (1965) and Gubler (1977). The effective range of a charge is given by the radius at which the additional stress in the snowpack caused by the detonation corresponds to the dynamic stress of a skier in a depth of about 0.5 m. Including a margin of safety the stress is assumed to be ~1500 Pa. Firing a 2.5 kg charge in a height of 1 m above the surface yields an effective range of ~40 m (Stoffel, 2001).

6.2 Backcountry travellers

The additional stress induced by e.g. a skier has been measured experimentally by Schweizer and Camponovo (2001). Depending on snow conditions and depth of the weak layer the additional skier induced dynamics stress is one the order of 200-1200 Pa.

6.3 Aircrafts

The noise caused by a jet plane that is taking off is about 120 dB in a distance of 60 m from the runway. This corresponds to an air overpressure of 20 Pa.

Perroud and Lecomte (1979) have investigated the pressure amplitudes on the ground caused by jets flying at supersonic speeds at 900 m above the ground. They cause a pressure jump, i.e. an abrupt pressure change within a short time interval. Twelve geophones were placed along the flight path on the snow surface and values between 200 Pa and even more than 500 Pa in the focal curve were obtained. They recorded two avalanches during 20 test flights on 7 days.

Measurements with geophones of the displacement velocities inside the snow cover caused by a nearby landing helicopter yielded $0.3\text{-}1.0\times10^{-5}$ m/s corresponding to a pressure amplitude of 10 Pa at most. The perturbation might have been caused by either the air pressure wave or seismic waves (van Herwijnen, personal communication).

Table 1: Pressure amplitude $\hat{p}$ of elastic waves caused by various sources.

source	$\hat{p}$ (Pa)
loud scream	2
jet plane	20
supersonic boom	200
detonation	>1500

6.4 Human voice

The typical acoustic power output of the human voice is about 10^{-5} W in conversation (Billingham and King, p. 44). The average maximum power of the human voice is about 2 mW corresponding to a pressure amplitude of 2 Pa.

7 AVALANCHE RELEASE

The deformation caused in the snow is proportional to the pressure amplitude of the wave at the snow surface (Gubler, 1977). As explosives and skiers are effective triggers and weak layer strength is often about 1 kPa (Jamieson and Johnston, 2001), short term pressure amplitudes of at least about 200-500 Pa are required to initiate a structural failure in the weak layer when the stability is marginal. Accordingly, higher amplitudes are required for less unstable conditions. The sound emitted by a person or even an aircraft is substantially below this value.

At times of high instability, when natural avalanches are frequently observed, a coincidence of shouting and release may occur, but it will not be possible to claim that the release had been caused by the shouting.

8 CONCLUSIONS

Based on order of magnitude estimates of the pressure amplitude of various sources that cause elastic or pressure (sound) waves it can be ruled out that shouting or loud noise can trigger snow slab avalanches. The amplitudes are at least about two orders of magnitude smaller than known efficient triggers. Triggering by sound really is a myth.

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