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Speed and attenuation of acoustic waves in snow: Laboratory experiments and modeling with Biot's theory

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ABSTRACT

Monitoring acoustic emissions (AE) prior to imminent failure is considered a promising technique for assessing snow slope instability. Gaps in elastic wave propagation characteristics in snow hinder quantitative interpretation of AE signals. Our study focuses on characterizing the propagation of acoustic reference signals in the ultrasonic range across cylindrical snow samples with varying density (240–450 kg m^{-3}). We deduced the acoustic attenuation coefficient within snow by performing experiments with different column lengths to eliminate possible influences of the snow-sensor coupling. The attenuation coefficient was measured for the entire burst signal and for single frequency components in the range of 8 to 35 kHz. The acoustic wave propagation speed, calculated from the travel time of the acoustic signal, varied between 300 m s^{-1} and 950 m s^{-1}, depending on the density and hardness of snow. From the sound speed we also estimated the Young's modulus of our snow samples; the values of the modulus ranged from 30 to 340 MPa for densities between 240 and 450 kg m^{-3}. In addition, we modeled the sound propagation for our experimental setup using Biot's model for wave propagation in a porous medium. The model results were in good agreement with our experimental results and suggest that our acoustic signals consisted of Biot's slow and fast waves. Our results can be used to improve the identification and localization of acoustic emission sources within snow in view of assessing snow slope instability.

1. Introduction

Snow avalanches present a significant hazard for human activity and infrastructure in snow-covered mountainous regions world-wide, yet, to date, the precise time and location of a single avalanche event remain unpredictable (e.g., McClung and Schaerer, 2006; Schweizer, 2008). For the prediction of instability of a snow-covered slope, suitable precursors must be identified. Among the most promising precursors are acoustic emissions (AE) generated during the formation of micro-cracks or the breaking of ice bonds within the snow (Reiweger et al., 2015; Reiweger and Schweizer, 2013). Current research efforts focus on the identification and localization of acoustic emission features preceding snow failure and avalanches. The knowledge of the speed and the attenuation of acoustic waves in snow is, however, a necessary prerequisite to increase the accuracy of event localization and to describe the mechanism of evolution of the acoustic signals from the emission to the detection.

Oura (1953) was among the first to measure the speed of sound in snow. Since then various studies were performed, but the results on the acoustic properties of snow widely vary depending on the measurement method. When piezoelectric sensors in direct contact to the snow were used, the obtained speed was higher than the sound speed in air and increased with increasing density (solid symbols in Fig. 1, Reiweger et al., 2015; Smith, 1965; Takei and Maeno, 2004; Yamada et al., 1974). When, on the other hand, the speed was measured with an impedance tube (Buser, 1986; Ishida, 1965; Marco et al., 1998) or with microphones not in direct contact with the snow's ice skeleton (Gudra and Najwer, 2011; Iwase et al., 2001; Lee and Rogers, 1985; Oura, 1953), the measured speed was lower than the speed in air and decreased with increasing density (open symbols, Fig. 1).

In Fig. 1, the values of the speed of sound previously determined in various studies are compiled as a function of snow density. As already shown by Sommerfeld (1982), three distinct speed patterns can be observed for densities higher than about 250 kg m^{-3}. Sommerfeld and Gubler (1983) connected them to longitudinal and transversal waves propagating in the ice skeleton (solid symbols, Fig. 1) and longitudinal waves propagating in the air phase (open symbols). Ishida (1965) showed that the speed in the air phase depends on the frequency in the range of 0.1 to 10 kHz and is proportional to the air permeability of snow. With increasing density the pore space becomes more tortuous and the air permeability decreases; accordingly the speed of the acoustic wave propagating in the air phase decreased (Ishida, 1965). Lee and Rogers (1985) suggested that a transition in the propagation phase

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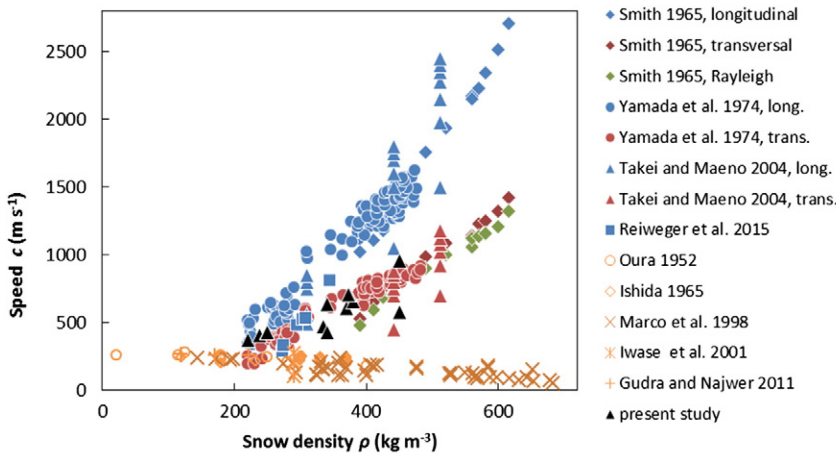

Fig. 1. Summary of sound propagation speed values from previous studies. The solid symbols represent values obtained with sensors in direct contact with the snow. The open symbols represent values obtained with microphones not in direct contact with the snow. Three different wave types were observed: longitudinal (blue) and transversal (red) waves propagating in the ice skeleton, and waves propagating in the pore space (orange). The green diamonds represent the measured velocities of Rayleigh waves (Smith, 1965). In addition, the results of our own measurements are shown (black triangles).

exists at a density of about 300 kg m^{-3}, with waves propagating mainly in the air phase for lower density and mainly in the ice skeleton for higher density snow. However, Marco et al. (1998) measured the speed of waves in the air phase at densities up to 680 kg m^{-3} contradicting the assumption of Lee and Rogers (1985). Takei and Maeno (2004) showed that the wave speed in the ice skeleton is determined by the elastic moduli of the snow, which are determined by the microstructure. The velocities of the longitudinal and transversal waves in the ice skeleton increased during temperature cycles due to the increased strength of the bonds between the ice grains. When the temperature approached 0 °C, the weakening of the bonds caused a drop in the wave speed. Yamada et al. (1974) found that the sound speed is anisotropic for anisotropic snow.

The attenuation of acoustic waves in snow was a topic of various studies in the past. The attenuation properties were usually either obtained from the transmission loss at different snow thicknesses (Gudra and Najwer, 2011; Ishida, 1965; Reiweger et al., 2015) or deduced from the measured impedance (Marco et al., 1998). Lang (1976), Johnson (1982), and Kapil et al. (2014) measured the attenuation of acoustic waves in snow without explicitly reporting the attenuation coefficient, but it can still be derived from their published data. The attenuation coefficient measured by the different authors was between 0.05 and 3.5 dB cm^{-1}. A direct comparison of the published values is difficult, since different methods were applied on different snow types in different frequency ranges. The attenuation was found to increase with increasing frequency (Ishida, 1965; Iwase et al., 2001) and also with increasing snow density (Gudra and Najwer, 2011; Ishida, 1965; Marco et al., 1998). Ishida (1965) suggested that the attenuation was inversely proportional to the square root of the air permeability.

Most previous models for sound propagation in snow assume a rigid ice frame (e.g. Buser, 1986). Buser (1986) reproduced the measured surface impedance with the model of Zwikker and Kosten (1949). The same model was used to investigate the relationship between acoustic properties and snow microstructure by Attenborough and Buser (1988) and Marco et al. (1998). Boeckx et al. (2004) applied the Johnson-Champoux-Allard model (Allard and Attala, 2009; Champoux and Allard, 1991; Johnson et al., 1987) to the propagation of sound above snow covered terrain. Maysenhölder et al. (2012) studied the relation between microstructure and sound absorption with the relaxation model of Wilson (1993, 1997). These models were successfully applied to experiments where the air–snow interaction was studied, although the ice frame is considered to be rigid. On the other hand, Biot's model (Biot, 1956a) takes into account the combined motion of the elastic ice frame and the pore fluid/gas and was applied to snow by Johnson (1982). It provides two types of longitudinal waves (fast and slow Biot's waves) and one type of transversal wave as it is experimentally observed. The experimental data available to Johnson (1982) tended to support the model predictions, but further experiments were required to properly evaluate Biot's model on snow. More recently, Sidler (2015) modeled the propagation of acoustic waves in snow with Biot's theory. He simplified the approach by expressing the many parameters required as a function of snow porosity only and found that for low-density snow (below 200 kg m^{-3}) the speed of the Biot's slow waves exceeds the speed of Biot's fast waves. This is in agreement with the experimental data presented in Fig. 1. Also the propagation of waves produced during blasting experiments was modeled above and inside the snowpack with Biot's model for the frequency range of 0 to 1 kHz (Sidler et al., 2016; Simioni et al., 2015). Sidler et al. (2016) successfully reproduced the acceleration measured in the snowpack and showed that the waves propagating through the pore space, i.e. slow Biot's waves, significantly contribute to wave propagation in snow due to an explosion.

The acoustic propagation properties can be used to derive different mechanical snow properties, e.g. the elastic moduli can be derived from the propagation speed (Smith, 1965; Takei and Maeno, 2004). The most basic method to measure Young's modulus is a direct mechanical test either quasi-static (Mellor, 1975) or dynamic (Sigrist, 2006). Alternatively, the elastic properties can be derived from micro-computed tomography images (Schneebeli, 2004), or derived from the snow micro-penetrometer (SMP) penetration force signal (Marshall and Johnson, 2009). The values obtained with the different methods differ substantially, e.g. the values obtained with the micro-computed tomography are about three orders of magnitude larger than the values derived from SMP signal (Reuter et al., 2013). The difference is attributed to the different strain rates and magnitudes of displacement applied during the different measurements. With some of the methods non-elastic deformation will be induced, typically resulting in lower values of the modulus. Alternatively, acoustic waves cause small strains at high rates in the elastic range. Therefore, the acoustic method for the derivation of the Young's modulus seems a feasible option, even superior to other methods. In particular, the AE method allows a non-destructive and in-situ characterization of the mechanical properties of snow.

The values of speed and attenuation of acoustic waves published in previous studies vary strongly with the snow properties and considerably depend on the measurement method employed. Most of the previous results were obtained at frequencies below 10 kHz, while recent