

PAPER

Audible sound under compressed snow simulating avalanche debris

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Abstract: To identify effective communication methods for rescuing victims buried in an avalanche, we investigate the acoustic transfer characteristics by simulating a snow avalanche to identify a method for effectively communicating with buried individuals. The results indicate that sound attenuation at a depth of 30 cm from the snow surface is 60 dB over a wide frequency range when the sound is emitted above the surface. Because the sound insulation of the simulated snow avalanche is extremely high, the sound emitted from the surface will likely not reach the buried victims. However, vibrations due to foot stomping on the surface of snow are likely to be transmitted to a buried individual as sound.

Keywords: Sound transmission, Snow, Avalanche, Stomping, Rescue

1. INTRODUCTION

Many snow avalanche accidents occur annually in the mountains during the winter. In a snow avalanche, victims are buried in snow, resulting in death by suffocation unless rescue is provided immediately after burial. The best method of estimating burial locations is to use an avalanche transceiver that detects the signal from avalanche transceivers held by the buried victims; however, avalanche victims do not always carry an avalanche transceiver. In such cases, acoustic cues are useful for localization. For example, using sound localization methods, eight completely buried victims were discovered to be alive in Canada during the years 1984–1996 [1]. In addition, a method of calling and listening in the absence of an avalanche transceiver was proposed and has been taught in training courses for avalanche rescue operations in Japan [2]. However, this method assumes that the human voice in the form of sound waves can be transmitted through a snow layer in the audible range.

The acoustic characteristics of snow have been extensively reported in previous studies. For example, Ishida and Onodera [3], Ishida [4,5], Ogaki and Takemura [6], Marco *et al.* [7], and Capelli *et al.* [8] investigated the sound absorption and impedance of homogeneous snow samples. Moreover, Takada *et al.* [9], Oura [10], Iwase *et al.* [11,12], and Tyagi *et al.* [13] investigated the sound absorption and velocity of snow in an actual field. These previous studies primarily focused on soft snow instead of the hard snow that is typically associated with avalanche debris. When a snow avalanche is initiated along a slope, the snow is soft and flows like a river. However, once the flow stops, the snow becomes considerably hard because of the combined effect of melting due to friction and the high pressure associated with the moving avalanche [14]. Therefore, findings concerning soft snow in previous studies may not correspond to the acoustic characteristics of hard avalanche snow. In other words, it is unclear whether sound waves associated with a rescuer's voice can be transmitted to the buried victims through the hard snow of avalanche debris. Iwase *et al.* [11,12] investigated the acoustic properties of hard snow; however, they did not report the snow profiles, such as the snow density. Therefore, it is difficult to consider the acoustic characteristics of avalanche debris using their data. In addition, if it is difficult for the rescuer to reach the victims buried in hard avalanche snow on the basis of their voice, then a viable method must be developed to inform the victims of the presence of the rescuers above the snow.

In this study, we measured the sound attenuation of artificially compressed snow simulating the hard snow of

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avalanche debris. Furthermore, we measured the profiles of the snow to evaluate the acoustic characteristics of snow avalanche debris and to estimate the pressure level of sounds transmitted through the snow debris. In addition, we measured the sound in the compressed snow during direct vibration due to foot stomping and thrusting with ski poles on the snow surface and calling out to communicate with the victims in the snow, as these are the actual and typical sound and vibration sources during rescue operations. Assuming a realistic avalanche rescue scene, the experiment was conducted in a field covered with snow instead of in a laboratory.

2. METHODS

2.1. Measurement Field and Flow

Acoustic measurements of snow were performed in a wide and flat field in Ishikari-gun, Hokkaido, Japan. The global positioning system (GPS) (Fortrex 301, Garmin) coordinates of the field were N43°28.013′, E141°34.960′, and its altitude was 122 m. A snow pit was dug to a size of 2.5 m (length) × 1.5 m (width) × 1.3 m (depth). The normal vector to the vertical face of the pit was directed to the west (Fig. 1). The total depth of the natural snow near the snow pit was 270 cm.

For comparison, we measured the sound attenuation of two types of snow: artificially compressed snow simulating the hard snow of avalanche debris and natural snow. Acoustic measurements were performed in the same field over a two-day period (February 22 and 23, 2012). Natural snow measurements were performed on the first day, whereas compressed snow data acquisition was conducted on the second day. Artificially compressed snow was produced by treading down snow immediately after the completion of the first day's measurements, and it was left overnight to allow the development of hard icy snow. This was performed to simulate the hard snow of avalanche debris (see Sect. 2.3).

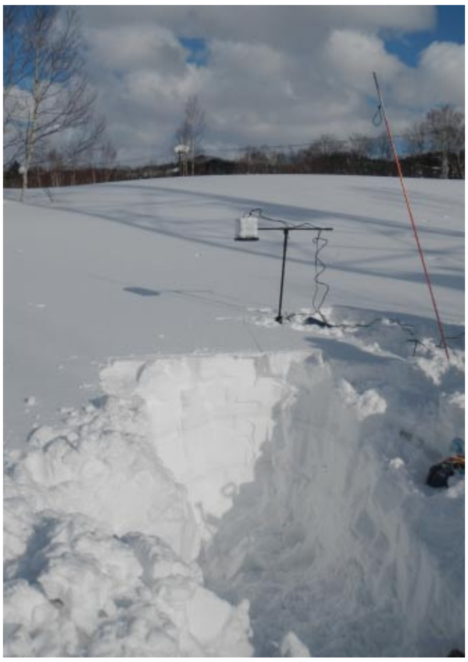

Fig. 1 Snow pit and loudspeaker for acoustic measurement.

2.2. Weather Conditions

The first day was fine in terms of weather but occasionally cloudy during the experiments (13:00–16:00) involving natural snow. According to AMeDAS weather data, the temperature of the area around the field varied from −1.4°C to 0.3°C, the wind speed ranged from 3 m/s to 5 m/s, and the wind direction was between W and WNW. On the second day, the weather was fine during the investigations (11:00–14:00) involving compressed snow. The temperature of the area around the field ranged from 0.7°C to 1.5°C, the wind speed varied from 2 to 3 m/s, and the wind direction was between E and ESE. No snow had fallen in the previous 24 h period, and the lowest recorded temperature at 03:00 of the previous night was −5.4°C.

2.3. Snow Profiles

A push-pull force gauge (PX50 with a 15-mm-diameter disc-shaped attachment, Aikoh Engineering) was used to measure the snow hardness. A snow sampler (Climate Engineering; volume: 100 cm^3, depth: 5.6 cm) and a digital hanging spring scale (WeiHeng; rated load: 5 kg, accuracy: 1 g) were used to measure the snow density. A digital thermometer (AND-5625, Andokeiki) was used to measure the snow temperature. Figure 2 shows the temperature, density, and hardness of the natural and compressed snow samples. In both cases, the snow was considered to be dry based on the temperature inside the snow and the observation of snow grains. Table 1 shows the snow type and grain size of the snow layers at various depths below the surface of the natural and compressed snow. According to the change in external air temperature and the temperature in the snow prior to the acoustic measurement (Fig. 2), it is likely that the snow condition did not change significantly during the acoustic measurement.

2.4. Acoustic Measurement

2.4.1. Sound and vibration sources

The sound source used for calculating the transfer functions of the snow was a time-stretched pulse (TSP), which is a frequency sweep signal with a flat and broadband power spectrum [15]. The TSP was synthesized digitally using a computer at a sampling rate of 48,000 Hz and a 16-bit resolution for 65,536 (2^{16}) points. This signal was stored in a linear pulse code modulation (PCM) recorder (DR-100 MKII, TASCAM) and then played back

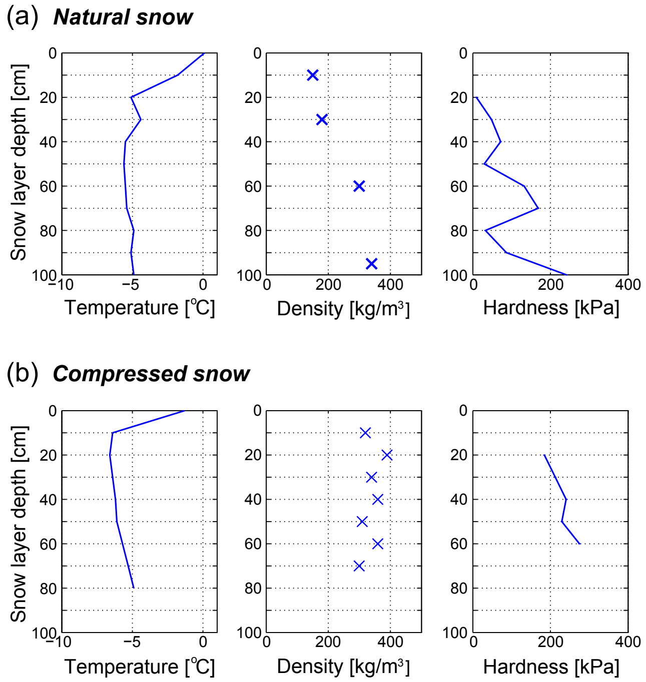

Fig. 2 Temperature, density, and hardness of natural snow (a) and compressed snow (b).

Table 1 Characteristics of natural snow (a) and compressed snow (b) as a function of depth from the surface. PP: precipitation particles, DF: decomposing and fragmented precipitation particles, RG: rounded grains.

(a) Natural snow

Depth from surface [cm]	Snow type	Grain size [mm]
0–20	PP	0.3
20–50	DF	0.5–0.7
50–85	RG	0.5–1.0
85–90	DF	0.5
90–110	RG	1.0

(b) Compressed snow

Depth from surface [cm]	Snow type	Grain size [mm]
0–10	RG	—
10–18	RG	—
18–58	RG	—
58–62	RG	—
62–70	RG	—
70–80	RG	—

and emitted from an active loudspeaker (C50A, Behringer) that was set facing downward at 90 cm above the snow surface (Fig. 3).

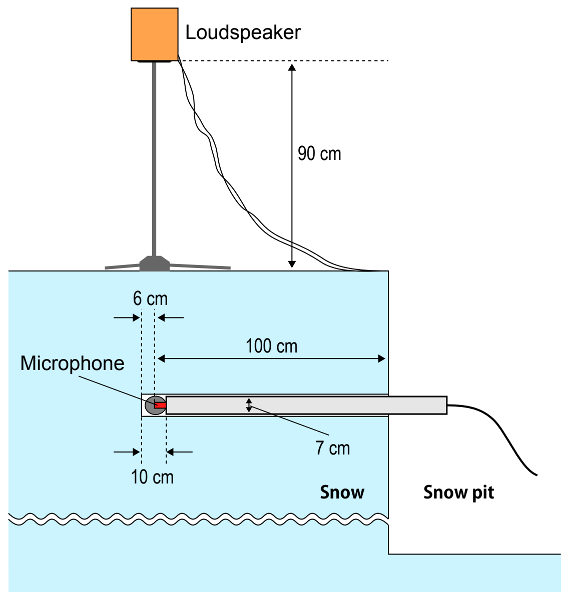

Fig. 3 Configuration of instruments for acoustic measurement.

In addition, the following sound and vibration sources were used to measure only compressed snow: a) two different whistles: a large whistle (Tornado No. 636, ACME; hereinafter “type A”) and a small whistle (FIN-345, FINE; hereinafter “type B”) blown 154 cm above the snow surface; b) the voice of a male subject with both hands cupped around the mouth, bent at the waist, and calling “Oi” toward the snow surface; c) stomping on the snow surface by two subjects: a male subject weighing 70 kg and a female subject weighing 50 kg. The subjects wore rubber-soled snow boots when stomping, and the strength of stomping was greater than that of walking, although not the maximum strength possible; and d) thrusting ski poles onto the snow surface.

2.4.2. Sound recording

A 1/2-inch condenser microphone (4006C, DPA) was positioned at the tip of a polyvinyl chloride cylindrical pipe with an internal diameter of 7 cm. The microphone capsule was shielded using a window screen to protect it from snow (see Fig. 3). A pipe was used to protect the connection cable and amplifier of the microphone. The internal space was filled with semi-hard polyurethane foam to provide adequate insulation from sound propagating through the pipe. The microphone was inserted horizontally into the snow at a distance of 1 m from the vertical face of the snow pit such that it was positioned immediately under the loudspeaker (Fig. 3). Depths of 15, 30, 60, and 100 cm below the surface were used for natural snow, whereas depths of 30 and 60 cm were used for compressed snow case. With compressed snow, it was not possible to set the depth of 100 cm, which was possible with natural snow, because the depth of the snow pit in compressed snow was shallower than that in natural snow (see Sect. 2.1). A depth of −4 cm (i.e., 4 cm above the snow surface) was used as the control. To analyze the effects of the horizontal distance between the microphone and the sound source, stomping was performed at 0 (directly above the measurement point), 100, and 180 cm away from the microphone in the direction opposite to the snow pit on a horizontal plane. Sounds were received by the microphone and recorded using a linear PCM recorder (DR-100 MKII, TASCAM) at a sampling rate of 48,000 Hz with a resolution of 16 bits. The background noise was recorded with the microphone for about 10 s at each depth in the snow without radiating sound from the loudspeaker.

2.4.3. Data analysis

In Sect. 3.1, we calculated the impulse response for a recorded TSP signal (see Sect. 2.4.3) applying the on time-stretched pulse theory [15]. Each impulse response was then truncated to 1,024 points using a Hamming window. The window was set such that the center was positioned at the maximum point of the impulse response. We calculated the frequency response from the impulse response via an 8,192-point fast Fourier transform (FFT).

In Sect. 3.2, each recorded signal was truncated to 16,384 points using a Hamming window. For foot stomping and ski-pole thrusting, the recorded signals resembled impulses (see top rows of Figs. 6(a) and 6(b)); hence, the window was set such that the center was positioned at the maximum point of the impulse-like signal. We calculated the frequency response from this signal by 65,536-point FFT at a sampling rate of 48,000 Hz. The amplitude spectrum obtained from the FFT was passed through a bank of rectangular bandpass filters with bandwidths similar to the critical bandwidths of the auditory system of human subjects. This was performed to eliminate the contributions of spectral details in the amplitude spectra that cannot be resolved in the human auditory periphery. For the center frequency f, the critical bandwidth BW, is expressed as $10\log_{10} BW = 8.3\log_{10} f - 2.3$, and BW is approximately 20% of the center frequency [16]. The frequency spectra of sound for the whistle, foot stomping, and ski-pole thrusting were obtained by averaging the spectra of more than 20 trials.

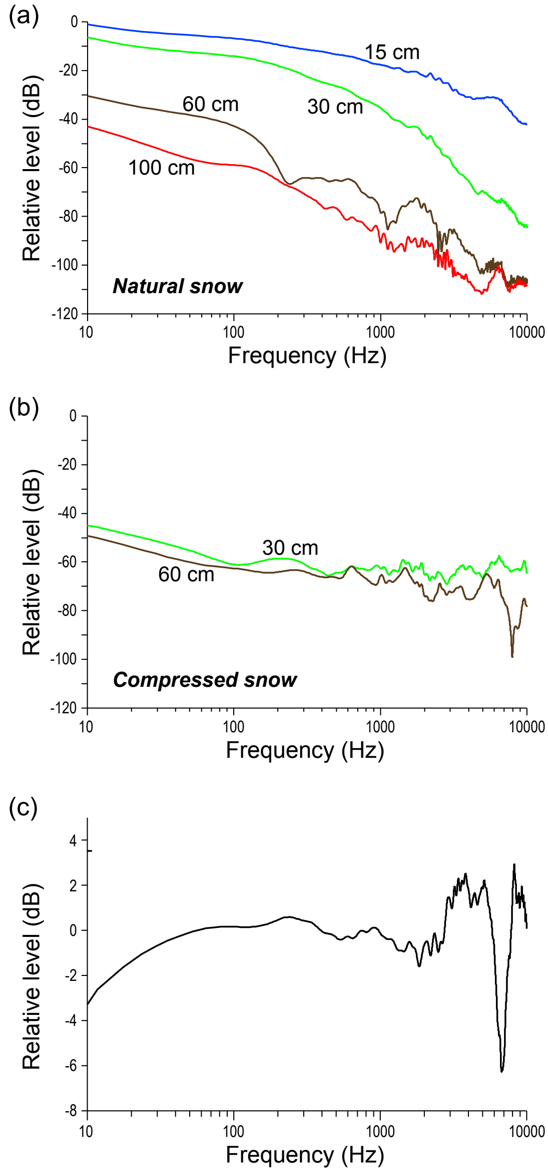

Fig. 4 Sound attenuation characteristics of snow and effects of sound reflected from snow surface. (a) and (b) show sound attenuation characteristics of natural snow and compressed snow, respectively. The distance shown represents depth from the snow surface. The vertical axis represents the relative level to the sound pressure level measured on the snow surface for each type of snow (precisely, 4 cm above the snow surface). The line in (c) shows the difference spectrum between frequency spectra of sounds measured in natural and compressed snow surfaces.

3. RESULTS

3.1. Sound Attenuation Characteristics of Natural Snow and Compressed Snow

Figures 4(a) and 4(b) show the sound transfer characteristics of natural snow and compressed snow, respectively, from the snow surface (precisely, 4 cm above the surface) to the measurement point inside the snow, when sound was emitted above the snow. In Figs. 4(a) and 4(b), the numbers indicate the depth of the measurement points in the snow relative to the surface.

In the case of natural snow (Fig. 4(a)), the amount of sound attenuation due to snow increased with the frequency and depth of the measurement point. For example, when the depth from the surface was 15 cm, the attenuation of the sound was approximately 5 dB at a frequency of 100 Hz; however, at the same depth, it was approximately 15 dB at 1,000 Hz. When the depth from the snow surface was increased to 100 cm, the attenuation at 100 Hz was approximately 60 dB and increased to approximately 80 dB at 1,000 Hz.

In the case of compressed snow (Fig. 4(b)), the frequency dependence of the sound attenuation was extremely low, unlike in the case of natural snow cover shown in Fig. 4(a). In addition, compared with the case of natural snow cover, the sound in the frequency region below 1,000 Hz attenuated significantly. For example, in compressed snow, the sound attenuation was 60 dB at a relatively shallow depth of 30 cm regardless of the frequency. Also, in compressed snow, the difference in sound attenuation at depths of 30 and 60 cm was approximately 5 dB, compared with approximately 20 dB for natural snow cover. Even at a depth of 60 cm in compressed snow, there was a margin for further attenuation by 30 dB or more with respect to the background noise level from 100 Hz to 7 kHz.

For both natural snow and compressed snow, the reference for evaluating the sound attenuation characteristics was set to 4 cm above the snow surface. Hence, to directly compare the acoustic attenuation characteristics of natural snow and compressed snow, the difference in acoustic reflectance between the two snow surfaces must be elucidated. The solid line in Fig. 4(c) shows the difference in the frequency spectra of sounds measured on the two snow surfaces derived by subtracting the frequency spectrum of sound recorded on the natural snow surface from that on the compressed snow surface. As shown in the difference frequency spectrum presented in Fig. 4(c), a shallow dip appeared at approximately 2 kHz and a distinct dip appeared at approximately 7 kHz; however, the maximum level difference for frequencies lower than 5 kHz was 3 dB. This indicates that, below 5 kHz, the difference in acoustic reflectance between the two snow surfaces did not significantly affect the sound attenuation characteristics, as shown in Figs. 4(a) and 4(b).

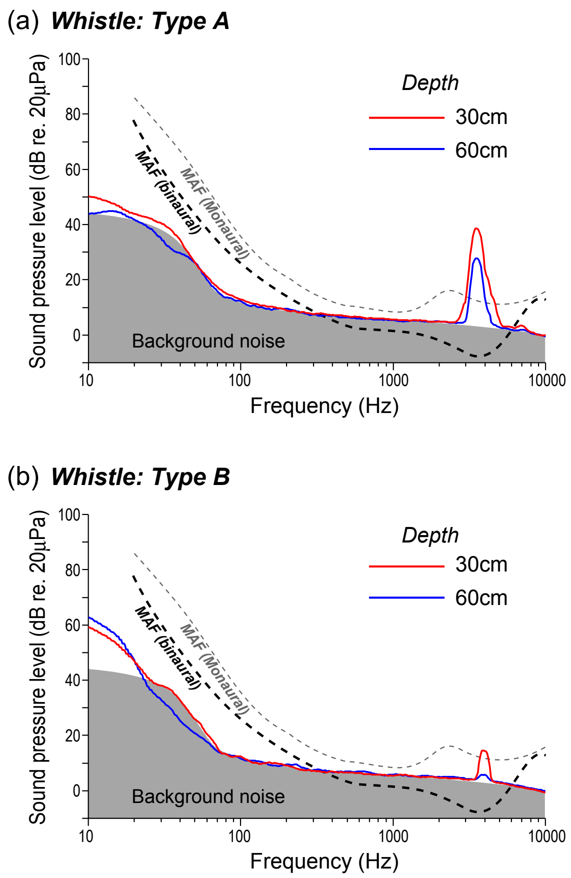

Fig. 5 Frequency spectrum of sound of whistles (types A and B) recorded in compressed snow. Sound recording points were directly under the whistle at depths of 30 and 60 cm from the snow surface.

3.2. Transmission of Sound and Vibration from Surface of Compressed Snow

In the case of compressed snow, to investigate the types of sound and vibration that can penetrate into the snow, we generated different sounds and vibrations on the snow and analyzed the propagation depth as audible acoustic waves.

3.2.1. Whistle sound and calling voice

Figure 5 shows the frequency spectrum of the sound of two whistles (types A and B), recorded in the snow at depths of 30 and 60 cm directly below the whistles. In Fig. 5, monaural and binaural minimum audible fields (MAFs) [17] are represented using different types of dotted line for reference.

The two types of whistle sound primarily comprised frequency components from 3,000 to 5,000 Hz. In the frequency spectrum of the sound captured in the snow shown in Fig. 5, peaks were observed near 4,000 Hz for both types of whistle. For type A, this peak value exceeded the monaural MAF even at a depth of 60 cm, whereas for type B, this peak value was less than the monaural MAF at the same depth. This implies that at a depth of 60 cm in the avalanche simulation, almost no sound can be heard from the type B whistle at this depth in the snow.

The calling voice was measured at depths of 30 and 60 cm. However, the sound signals were extremely weak and could not be measured at either depth. This implies that, in compressed snow, the sound of the human voice is barely audible, even at a depth of 30 cm.

3.2.2. Foot stomping and ski-pole thrusting onto surface

Stomping on compressed snow as well as thrusting ski poles onto the snow surface can result in the transmission of vibrations.

Figure 6(a) shows the partial time waveform and frequency spectrum of the stomping sound recorded in the snow. The measurement points of sound in the snow were set immediately under the stomping position at depths of 30 and 60 cm from the surface. When a man stomped on the snow (Fig. 6(a), blue line), the measured sound

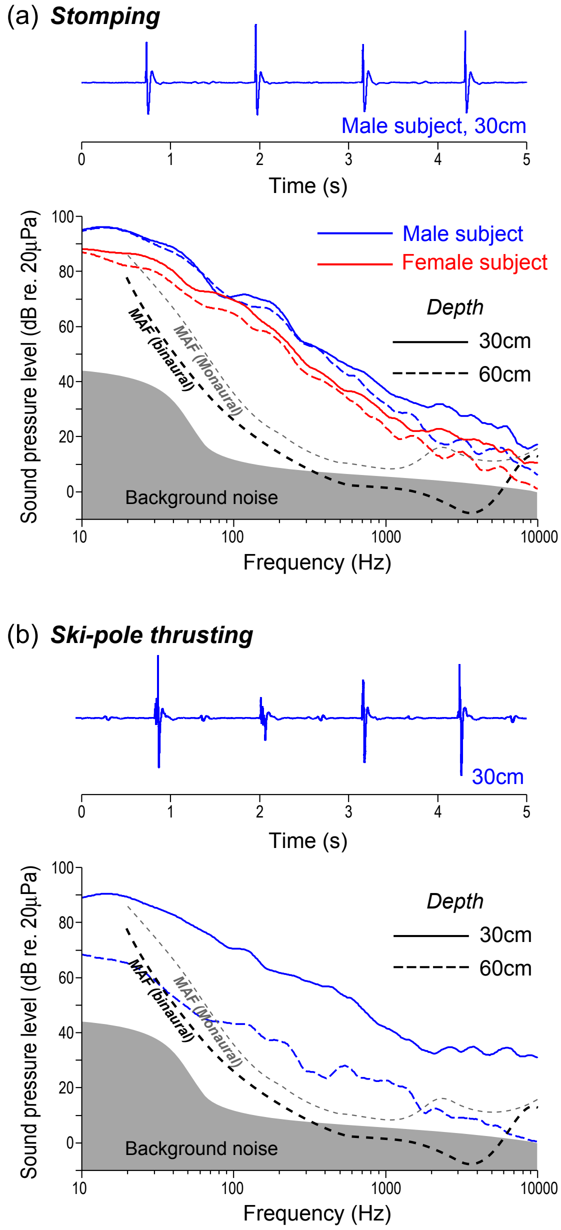

Fig. 6 Partial time waveform and frequency spectra of sound of foot stomping (a) and ski-pole thrusting (b) recorded in snow at depths of 30 and 60 cm from snow surface immediately under position of foot stomping and ski-pole thrusting. Amplitudes of time waveforms shown in (a) and (b) are relative values; therefore, the two amplitudes cannot be compared.

pressure level in the snow was much greater than the monaural MAF over a wide frequency band, even at a depth of 60 cm. For example, at 500 Hz, the sound pressure level of the detected acoustic wave was approximately 30 dB higher than the monaural MAF. When stomping was performed by a woman (Fig. 6(a), red line), the measured sound pressure level was approximately 10 dB lower than that for the man, but the measured value exceeded the monaural MAF over a wide frequency band. These results indicate that audible sounds generated by foot stomping are likely to be detected by buried victims, regardless of whether stomping is performed by a man or a woman. Figure 6(b) shows the partial time waveform and frequency spectrum of sound recorded in the snow for ski-pole thrusting. The measurement points in the snow were set at depths of 30 and 60 cm from the surface, immediately under the thrusting position. Whether it was a man or a woman performing the thrusting action, the recorded sound was the same; therefore, only data for the man are presented in the figure.

The frequency spectrum of the sound generated by ski-pole thrusting at a depth of 30 cm (Fig. 6(b)) is highly similar to that of a man stomping (compare the solid blue line in Fig. 6(a) and the solid line in Fig. 6(b)). However, compared with the case of stomping, the maximum difference in sound pressure level between the depths of 30 and 60 cm was 20 dB over a wide frequency range. For foot stomping, the maximum difference between sound pressure levels at the same depth was 10 dB for a similarly wide frequency band. Therefore, unlike foot stomping, for ski-pole thrusting, the frequency range that exceeded the monaural MAF was limited to 100–1,000 Hz at a depth of 60 cm, and the sound pressure level exceeded the MAF by 15 dB or less. These results indicate that at significant depths, foot stomping is more promising than ski-pole thrusting for delivering vibrations through snow.

The peak value of the pulse-like wave of stomping and thrusting changed with each action (see top panels in Figs. 6(a) and 6(b)). The coefficients of variation (i.e., SD/mean) from the peak values of multiple pulse-like waves ($N = 20$–30) were 0.45 and 0.35 at depths of 30 and 60 cm, respectively, for foot stomping by a woman, whereas they were 0.20 and 0.30 for a man, and 0.63 and 0.26 for ski-pole thrusting.

3.2.3. Distance effect of foot stomping

As presented in Sect. 3.2.2, vibrations caused by stomping on snow are likely to be heard as sound in compressed snow. However, the effect of the horizontal distance from the measurement point was not considered. Therefore, stomping was performed at different positions on a horizontal plane away from the measuring point (see Sect. 2.4.2).

Figure 7(a) shows the frequency spectrum of the sound recorded at a depth of 60 cm for a man stomping at a specified distance, and Fig. 7(b) shows that for a woman. For both a man and a woman, the sound pressure level decreased uniformly as the stomping position was moved further from the measuring point. When stomping was performed by a man, the sound pressure level exceeded the monaural MAF by approximately 15 dB in the range of 100 to 1,000 Hz, even at a distance of 180 cm. When stomping was performed by a woman, the frequency spectrum level exceeded the monaural MAF at a distance of 180 cm, as in

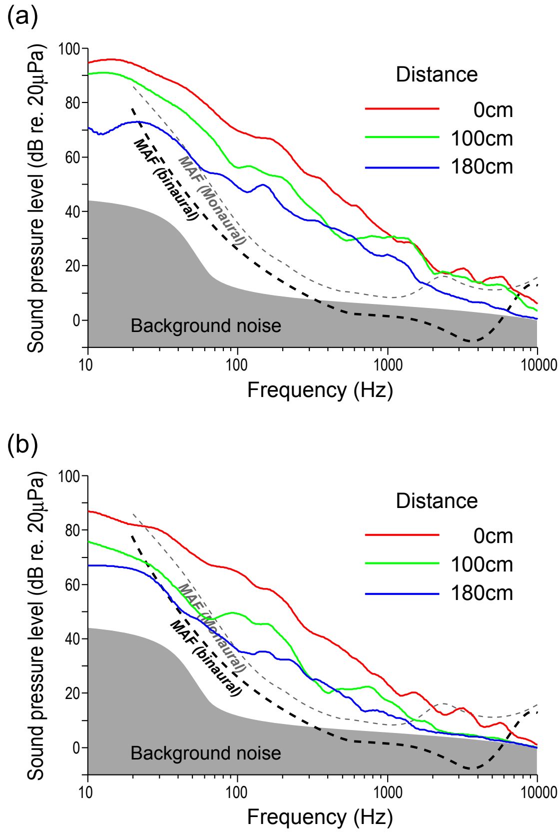

Fig. 7 Frequency spectrum of foot stomping sound by (a) man and (b) woman recorded in compressed snow. The distances between foot stomping and recording points in the horizontal plane were 0 (directly above the recording point), 100, and 180 cm. The depth of the recording point in snow was 60 cm from the snow surface, regardless of distance.

the case of a man. However, the amount in excess of the MAF was smaller than that for the man by approximately 10 dB. This indicates that a heavier body and greater physical strength are advantageous when attempting to transmit sound into the snow by stomping at a distance from the intended point.

4. DISCUSSION

4.1. Sound Attenuation Characteristics of Natural Snow and Compressed Snow

The attenuation of sound in natural snow became greater with higher frequency and deeper measurement point (Fig. 4(a)). This attenuation tendency resembled the experimental results in previous studies [3–13]; however, the attenuation magnitude in this study was not the same as that in previous studies. For example, the attenuation magnitude in this study was approximately 20 dB higher than that reported by Iwase *et al.* [11,12] over the frequency range from 100 to 1,000 Hz. This difference in attenuation value was assumed to be due to differences in the characteristics of natural snow, such as the number of snow layers, density, and hardness, even at the same depth. Although the measurements in this study only partially reflect the sound attenuation characteristics of natural snow, it can be said that the basic sound attenuation characteristics in terms of the analytical frequency and measured depth are the same regardless of the type of natural snow.

In this study, to simulate avalanche debris, snow was sintered by leaving firmly treaded snow overnight. The snow density at the time of measurement was 300–400 kg/m^3 regardless of depth (see Sect. 2.3). Avalanche debris generally has a density of 400–500 kg/m^3, and a maximum density of 800 kg/m^3 has been recorded [7,18]. Therefore, it can be inferred that the simulated avalanche snow in this study can represent avalanche debris. In the snow avalanche simulation, it was discovered that a sound attenuation of approximately 60 dB or higher occurred regardless of the frequency, even at a relatively smaller depth of 30 cm. This sound attenuation was much higher than that of natural snow, particularly at low frequencies of 1 kHz or less and at small depths of 60 cm or less. The snow density and hardness of the simulated avalanche snow were higher than those of natural snow (see Fig. 2); hence, it can be inferred that the significant sound attenuation of the simulated avalanche snow was primarily due to the high density and hardness of the snow.

As an example, when the sound attenuation of the simulated avalanche snow at a depth of 30 cm is converted into the sound-proofing performance of ordinary concrete, it corresponds to a concrete thickness of 70 cm or more for 125 Hz and about 30 cm for 1,000 Hz [19]. Also, in the case of the simulated avalanche snow at a depth of 30 cm, the measured sound attenuation is higher than the sound transmission loss calculated from the surface density of the snow using the mass law, which is as much as 25 dB in the low frequency range above 125 Hz. Hence, it can be inferred that the simulated snow avalanche or avalanche debris has an extremely high sound attenuation. Furthermore, debris with a density of 400 kg/m^3 or more is expected to exhibit even higher sound attenuations.

The difference in sound attenuation between the depth of 30 cm and 60 cm was about 5 dB under the compressed snow condition and about 20 dB under the natural snow condition. This difference in sound attenuation between two snow conditions was not due to a simple measurement issue, such as a signal-to-noise ratio problem. The reason why the difference between 30 cm and 60 cm is small under the compressed snow condition is unknown, but it will be necessary to clarify it in future experiments.

In the difference spectrum between frequency spectra of sounds measured under natural and compressed snow surfaces presented in Fig. 4(c), the dips appeared at about 2 kHz and 7 kHz. Under both the natural and compressed snow conditions, there were also dips at about 2 kHz and 7 kHz in the frequency spectra of the sound measured 4 cm above the snow surface, which were simply caused by interference between the direct sound and the reflected sound from the snow surface. These dips under each snow condition were the origin of the dips in the difference frequency spectrum shown in Fig. 4(c). Also, since these dips in the difference frequency spectrum were formed below 0 dB, it can be inferred that the acoustic reflectance of the compressed snow surface is higher than that of the natural snow surface. However, the fact that the difference frequency spectrum was less than 0 dB below 50 Hz is probably due to another cause, not the effect of the sound reflected from the snow surface.

4.2. Audible Sound under Avalanche Debris

4.2.1. Sound from snow surface

Avalanche burial relief is necessary when people are buried in snow at depths exceeding 30 cm. In the simulated avalanche snow, the sound attenuation was 60 dB or higher regardless of the frequency, even at a depth of 30 cm. In this study, we sounded voice calls toward the snow surface and recorded the detected sound at depths of 30 and 60 cm. However, no signals were detected. Considering the results of this measurement and the sound attenuation from the avalanche simulation (see Sect. 3.1), it can be concluded that any voice from the surface barely reaches a victim buried in an avalanche.

The whistle used is portable and can generate a loud sound without physical exertion in place of a voice call. For large whistles, the sound generated above the snow surface was louder than the monaural MAF at approximately 4,000 Hz, even at a depth of 60 cm (see Sect. 3.2.1). This indicates that whistle sounds may be heard in snow under certain avalanche debris conditions. However, when the snow depth is greater than 60 cm or when the snow density is higher than the avalanche simulation condition, coupled with the inherent limited frequency band of the whistle, the possibility of the whistle sound reaching the buried person is considered to be low. Sounds emitted in a space above a snow surface, such as a human voice or the sound of a whistle, are not likely to reach into the snow because acoustic waves cannot vibrate easily in snow of high density and mass, such as avalanche debris.

4.2.2. Vibration on snow surface

It was demonstrated that foot stomping on snow is likely to be heard as sound at a depth of 60 cm (see Sect. 3.2.2). However, the sound heard owing to vibrations from ski-pole thrusting onto the snow surface was similar to that generated by the stomping motion for small depths (up to 30 cm); however, for larger snow depths, the sound generated by acoustic waves from ski-pole thrusting is less likely to be heard compared with that generated by stomping. The ski-pole thrusting motion was inferior to the stomping motion in terms of the vibration transmission capability in the snow despite the similar vibration patterns; this is because the vibration energy added to the snow surface by the ski pole was less than that due to foot stomping. Therefore, to vibrate debris of high density and mass, foot stomping is advantageous compared with ski-pole thrusting, although it requires more energy than ski-pole thrusting.

It was shown that stomping was likely to be heard as sound at a depth of 60 cm, even when stomping was up to 1.8 m away from the measuring point (see Sect. 3.2.3). When a man stomps, sound is likely to be detected in the snow even at distances up to 3 m from the victim. In addition, because the stomping action does not require any tools, it is the most useful method for conveying the rescuer's position. To convey the presence or location of a searcher, snow vibrations caused directly by foot stomping are more effective than other sounds, such as voice calls above the surface. This is analogous to a person locked in a room being able to convey their presence more effectively to someone on the outside by directly hitting the door instead of shouting. Although the stomping strength changes with every step (see Sect. 3.2.2), it can be regarded as an effective transmission method if sound is delivered to the buried victims once at certain intervals.

To transmit the vibration caused by stomping into the snow, the hardness of the snow surface, which is the source of the vibration, is important. It is known that avalanche debris is composed of very hard and dense snow, including the surface [18]. Thus, it can be inferred that stomping is effective even in an actual avalanche situation. In the introduction, we introduced an example of victim rescue via sound localization performed in Canada. It is highly likely that the sound source in the example included not only the rescuer's voice, but also the rescuer's footsteps. This is because the rescuer's footsteps occur naturally and are transmitted into the snow, enabling the buried victims to hear them as sound.

4.3. Acoustic Cues for Rescue from Avalanche Burials

This study revealed that the acoustic properties of simulated avalanche snow differ significantly from those of naturally accumulated snow. Furthermore, to convey the presence of a rescuer to a buried victim using acoustic information, it was demonstrated that foot stomping on snow was more effective than a voice call or whistle sound.

The condition of debris in an avalanche varies depending on factors such as season, topography, temperature, humidity, and the cause of occurrence. Therefore, the results of avalanche simulation in this study cannot be considered a general theory of the acoustic properties of avalanche debris. Although only one of the numerous possible conditions of debris was investigated, the results clearly highlighted the ineffectiveness of voice calls and the effectiveness of footsteps for conveying the position and presence of a potential rescuer to a buried individual.

5. CONCLUSION

To identify effective communication methods for rescuing buried victims in an avalanche, we investigated the acoustic transfer characteristics of simulated avalanche snow and investigated several approaches for acoustic communication. The results indicated that the sound attenuation at a depth of 30 cm below the surface of snow was approximately 60 dB over a wide frequency range when the sound was emitted above the surface. The sound insulation by snow in the avalanche simulation was extremely high. Therefore, the transmitted sound above the snow surface will likely not reach the victim. However, it was shown that vibrations due to foot stomping on snow were likely to reach the buried person as sound.

Hence, we can conclude that stomping on the snow surface is more effective than emitting voice sounds or whistle sounds for conveying the presence of the rescuer to an individual buried under an avalanche.

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