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Detection of buried snowpack in landslide sediments using ground penetrating radar

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ABSTRACT

When landslides occur in snow-covered areas, the presence of snow may cause a secondary hazard. In the Tatsunokuchi area of Tsunan-machi, Niigata Prefecture, Japan, a large landslide was induced by the seismic motion resulting from the North Nagano Prefecture earthquake (magnitude of 6.7) on March 12, 2011, which caused a snow avalanche at the same time.

In this study, a ground penetrating radar (GPR) survey was applied to find areas of buried snow and ice underground in the landslide area. We first conducted experimental field surveys of artificially buried snow and ice to verify the effectiveness of the GPR survey in terms of investigating ice and snow within collapsed land. The results of the experiments successfully detected strong radar reflections from areas of ice and snow. When the ice and snow began to melt, the survey data showed both multiple reflections and the attenuation of reflections by meltwater.

Then, we investigated the presence of buried snow in the landslide area of Tatsunokuchi using GPR surveys. A GPR survey conducted in August 2011, five months after the landslide event, showed a clear response indicating the presence of a snowpack underlying the sediment. A response related to an underground snowpack was also observed in November 2012, about one year after the first GPR study. An excavation was conducted and the underground snowpack was ascertained. The snowpack was found to be compressed into an ice-like state that may be appropriate for long-term storage underground. The survey results of the buried snowpack in the landslide area at Tatsunokuchi were consistent with the results of the experimental surveys. Snowmelt water may cause the ground to loosen, which can increase the risk of secondary hazards such as subsidence and sediment discharge by heavy rains.

The results of our study indicate that GPR surveys are useful for examining buried snowpacks in landslide areas, as well identifying the potential areas where secondary hazards can be caused by the melting of snow and ice within the landslide area.

Keywords: Ground Penetrating Radar, Landslide, Snowpack, North Nagano Prefecture Earthquake

1. Introduction

There have been many earthquakes and related sediment hazards such as slope failure in Japan. Landslides that occur during heavy winter snowfall may lead to accumulation of the snow within the collapsed mass. The snow beneath the landslide area may then cause secondary hazards because of the meltwater causing the ground to loosen and subside. In landslide areas involving snow, it is important to investigate the condition of the snowpack to avoid secondary hazards.

In Tsunan-machi, Niigata Prefecture, a large landslide was induced by the seismic motion of the North Nagano Prefecture earthquake, a 6.7 magnitude earthquake that occurred on March 12, 2011. Following the earthquake, a mudslide, consisting of mud and snow, was induced, causing large damage around the lower reaches of the slope. In August 2011, snow was observed in the damaged area, which was considered to have remained buried underground since the hazard.

A GPR survey identified its utility by detecting the change in snow density, the snow depth and the number and thickness of the internal ice layers (Sakai et al., 1999).This method has been widely used in the field of glaciology to study frozen river lagoons, seasonally frozen ground and so forth (Moldoveanu et al., 2004, Nakano et al., 2008).

In the previous GPR researches, there has been little study on underground snow.

In this study, we conducted GPR surveys of areas where ice and snow were buried underground experimentally, and verified the effectiveness of this non-destructive survey method. After that, we investigated the landslide hazard area by GPR survey in August 2011 and in November 2012.

2. Outline of GPR survey

A GPR survey is a method of locating underground structures by detecting the physical response (e.g. reflection, penetration, and attenuation) of radio waves (Fig. 1). The depth range and the resolution depend on the frequency of the GPR antenna. When the frequency is higher, the resolution improves, but the depth range decreases. In our GPR surveys, we used the Noggin plus, the pulse EKKO 1000 and the pulse EKKO Pro (Sensors & Software Inc., Canada). Several types of antennas with different center frequencies were used.

We analyzed the survey data using GPR profiles that place the travel time of radio waves and the amplitude of reflection waves in chronological order. The vertical axis of the profile shows the travel time of the radio waves and the estimated depth, while the horizontal axis shows the distance along the survey line. In the profile, the grades of shading represent the amplitude difference of reflected waves. The peaks of waves are colored red, the troughs are blue and the even waves are white.

A topographical correction to the GPR profile was necessary because the study area was a slope. We measured the elevation of the survey line by D-GPS and corrected the effect of the surface slope on the GPR profile. Furthermore, we used timeslice mapping to create horizontal distribution maps of the reflection amplitude from all GPR profiles (Conyers and Goodman, 1997). We created timeslice maps at several depths using different colors to represent the strength or weakness of the reflected waves.

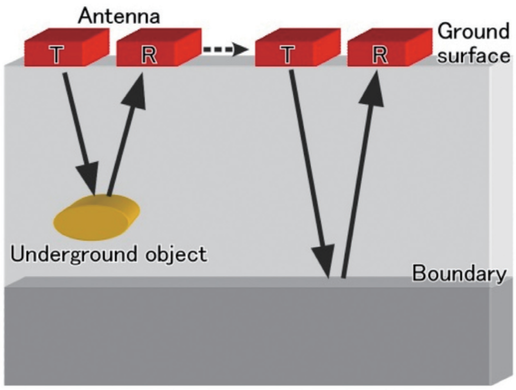

Fig. 1. Diagram of GPR survey

3. Experiment with buried snow and ice

To verify the effectiveness of GPR surveys as a method of detecting ice and snow in collapsed land, we conducted an experimental field survey of artificially buried snow and ice.

The experiment was conducted twice, in the summer and winter. Ice was buried during the summer experiment, while snow was buried during the winter experiment. The velocity of the radar waves was estimated from the depth of the buried samples.

3.1. GPR experiment with buried ice

A GPR survey of the experimental buried ice was conducted at Hodaka Observatory of Kyoto University in September 2011. We set up a survey area of 2m×2m and buried a block of ice with dimensions of 0.5m(W)×0.4m(D)×0.2m(H) in the center of the survey area (Fig. 2). The top surface of the ice was a few centimeters below ground and the soil in that region was categorized as humus. The survey lines were set at intervals of 0.25m and a 500MHz antenna (Noggin plus) was used for the survey.

We conducted a GPR survey of the area described above for the following three cases:

(1) No ice

(2) Buried ice

(3) Buried ice containing water that represented the state of water on the surface of ice

Fig. 2. GPR survey of the buried ice and the survey lines.

Figure 3 shows the GPR profile for all three cases, with the survey line crossing the middle of the area of buried ice and water. In the GPR profile for case (1), there was no significant anomaly. In the GPR profile of case (2), a strong reflection of radar waves appeared at the ice area, marked as the black dashed area in the figure. In the GPR profile of case (3), multiple reflections were observed because of the reflection of ice in addition to that of the water.

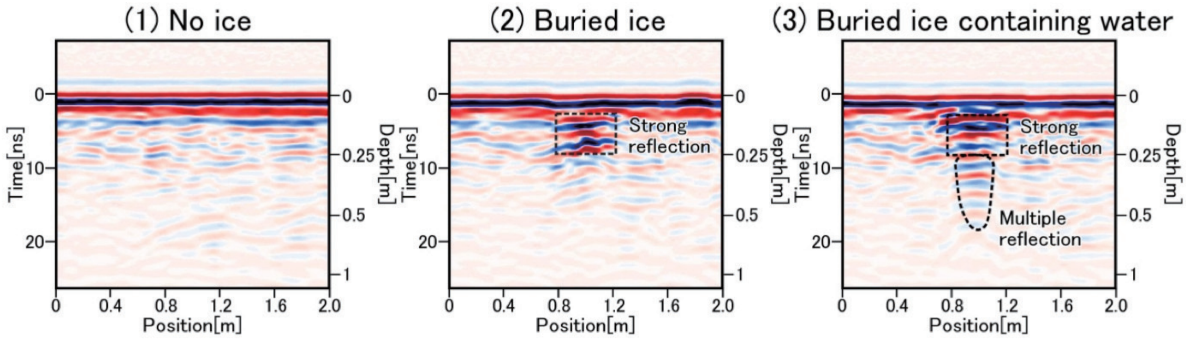

Fig. 3. GPR profiles: (1) No ice, (2) Buried ice, (3) Buried ice containing water

We constructed timeslice maps from the GPR profiles at depths of 0.12-0.3m (4-10ns), which were calculated by the thickness of the ice and underground depth, for the three cases (Fig. 4). An area of strong reflection appears at the buried ice area in case (2). The timeslice map of case (3) shows that the strong reflection caused by the buried ice was attenuated by the presence of water.

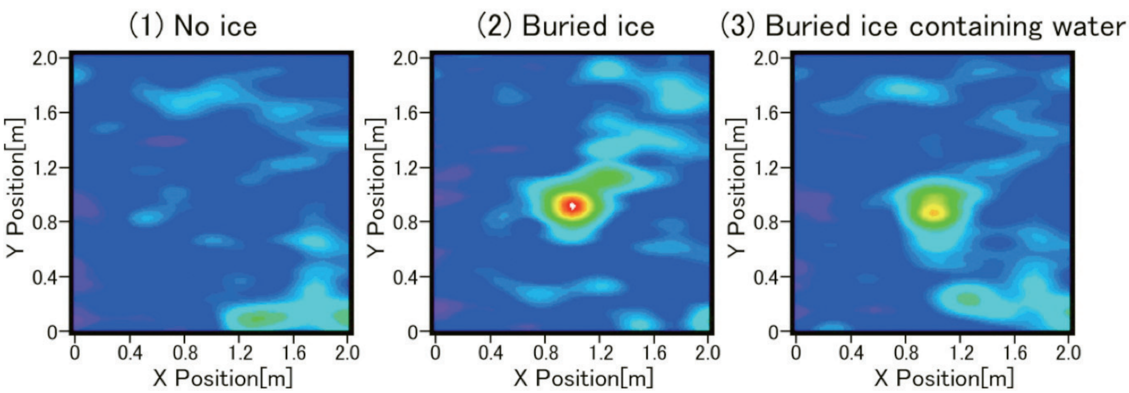

Fig. 4. Timeslice maps at a depth of 0.12-0.3m (4-10ns): (1) No ice, (2) Buried ice, (3) Buried ice containing water.

3.2. GPR experiment with buried snow

A GPR survey of the buried snow was conducted at a field site, with the humus soil mixed with red soil, in Toyama city in March 2012. We set up a survey area of 1m×1m and buried a block of compressed snow with dimensions of 0.2m(W)×0.2m(D)×0.15m(H) in the center of the survey area (Fig. 5). The top surface of the snow block was a few centimeters below ground. The snow had a density of 592.6kg/m3, temperature of 0°C and water content of 3.1%. The survey lines were set at intervals of 0.1m and a 1200MHz antenna (pulse EKKO 1000) was used.

We conducted the GPR survey on the area described above for the following three cases:

(1) No snow

(2) Immediately after snow was buried

(3) 15 minutes after snow was buried

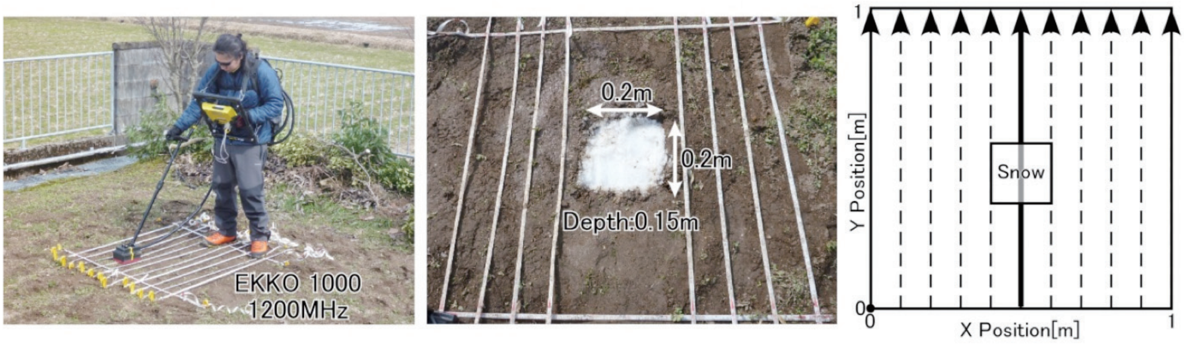

Fig. 5. GPR survey experiment of the buried snow and the survey lines.

Figure 6 shows the GPR profile for the three cases where the survey line crosses the middle of the area of buried snow. In the GPR profile of case (1), there was no significant anomaly. In the GPR profile of case (2), a strong reflection of radar waves appeared at the area of snow, marked as the black dashed area in the figure. In the GPR profile of case (3), multiple reflections from snow appeared, in addition to reflections from snowmelt water.

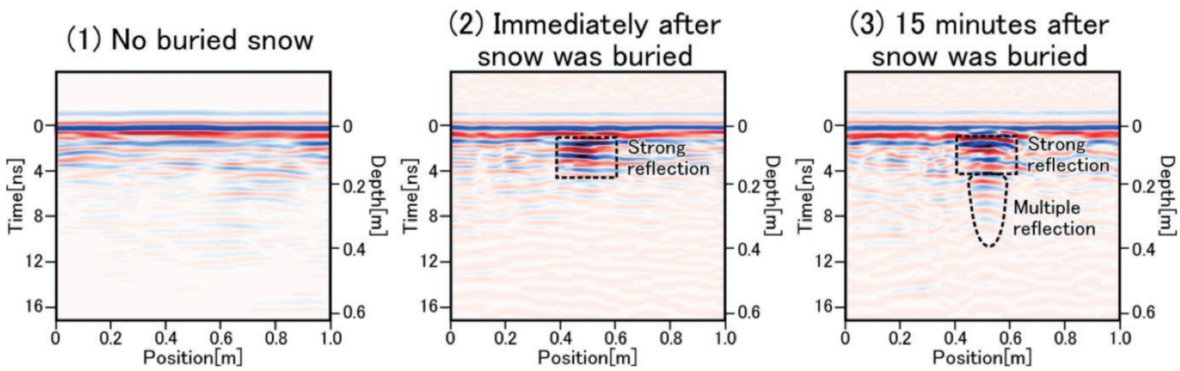

Fig. 6. GPR profiles: (1) No snow buried, (2) Immediately after snow was buried and (3) 15 minutes after snow was buried.

We constructed timeslice maps from the GPR profiles over a depth range of 0.06-0.18m (2-5ns), which were calculated by the thickness of ice and underground depth, for the three cases (Fig. 7). An area of strong reflection appears at the buried snow area in the timeslice map of case (2). The timeslice map of case (3) shows that the reflection caused by the snow area was attenuated due to the snowmelt water.

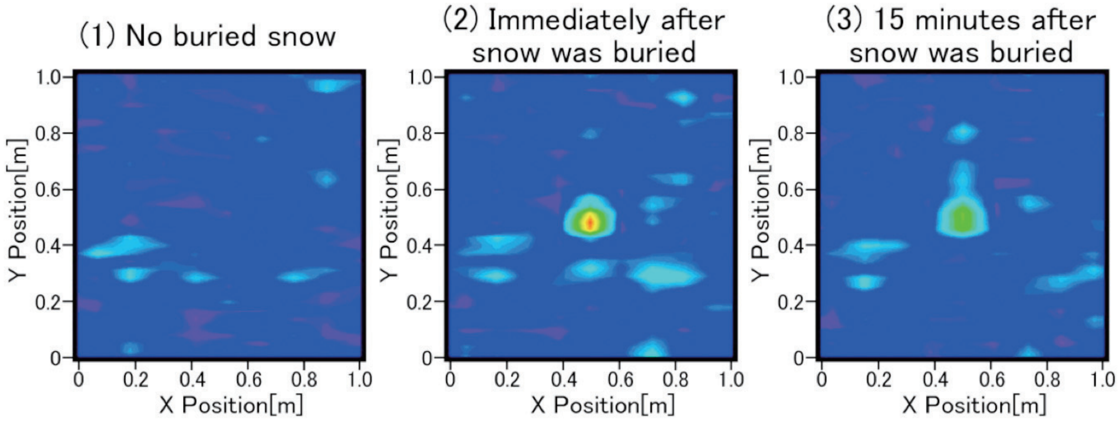

Fig. 7. Timeslice maps (2-5ns: 0.06-0.18m): (1) No buried snow, (2) Immediately after snow was buried and (3) 15 minutes after snow was buried.

4. Survey of snowpack in the sediment

4.1. Outline of survey

During the North Nagano Prefecture earthquake on March 12, 2011, the seismic motion induced a large landslide over an area of 130m×130m on the northeast slope of Eboshigatayama of the Tatsunokuchi area in Tsunan-machi. The landslide moved downslope about 760m over a width of 50-100m, covering Route 353 with mud consisting of a mixture of snow and soil (Kamiishi et al., 2012; Hoyanagi et al., 2012). Figure 8 shows the condition of the field site in August, five months after the landslide event. A snow block was observed at the site, which indicated that the landslide sediment may contain a snowpack.

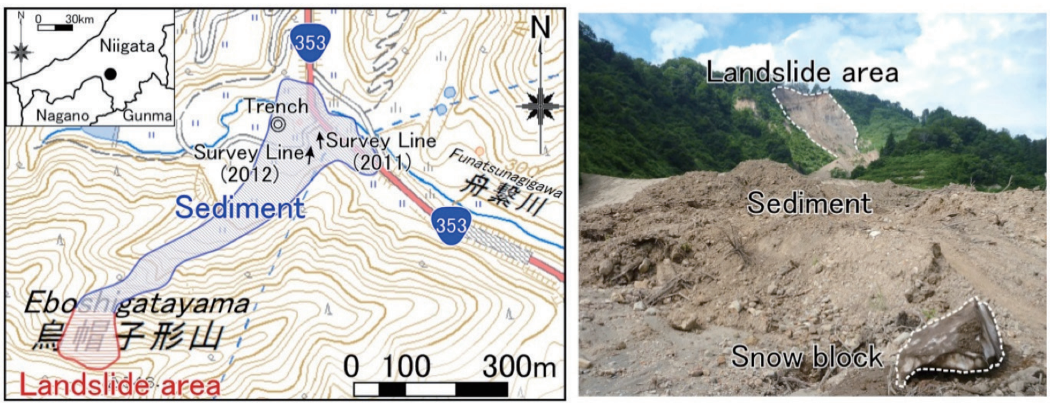

Fig. 8. Map of the Tatsunokuchi area and photograph of the landslide area. The arrows of the figure on the left show the survey lines. The arrow's length is the distance of the lines. The arrow's direction is the surveyed course. ◎ is the excavation point.

4.2. Result

(1) GPR survey in August 2011

A GPR survey of the collapsed sediment was conducted about 700m from the landslide area. We set a survey line length of 36.5m and used two types of antennas with center frequencies of 250MHz (Noggin plus) and 100MHz (pulse EKKO Pro) because the depth of the buried snow was unclear. A photograph of the survey in August 2011 and elevation of the survey line are shown in Fig. 9.

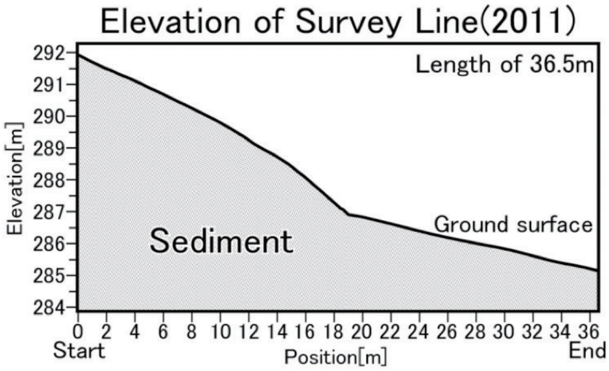

Fig. 9. Photograph of survey in August 2011 and elevation of the survey line.

The average velocity of the radar waves was calculated to be 0.06m/ns using a common mid-point (CMP) survey (Annan and Cosway, 1992), and the velocity was used to draw the GPR profile. Figures 10 (a) and 10 (b) show the GPR survey profiles using the 250MHz and 100MHz antennas, respectively. In both the profiles, strong reflections of radar waves were identified at a distance of 14-24m from the starting point of the survey. The profile from the 100MHz antenna showed a clearer reflection than that from the 250MHz antenna. As the snowpack in the ground showed as strong reflections from our experiment, the reflection of the radar in these profiles was possibly due to the snowpack area. The area marked by dashed lines in Fig. 10 is the estimated snowpack area under the sediment.

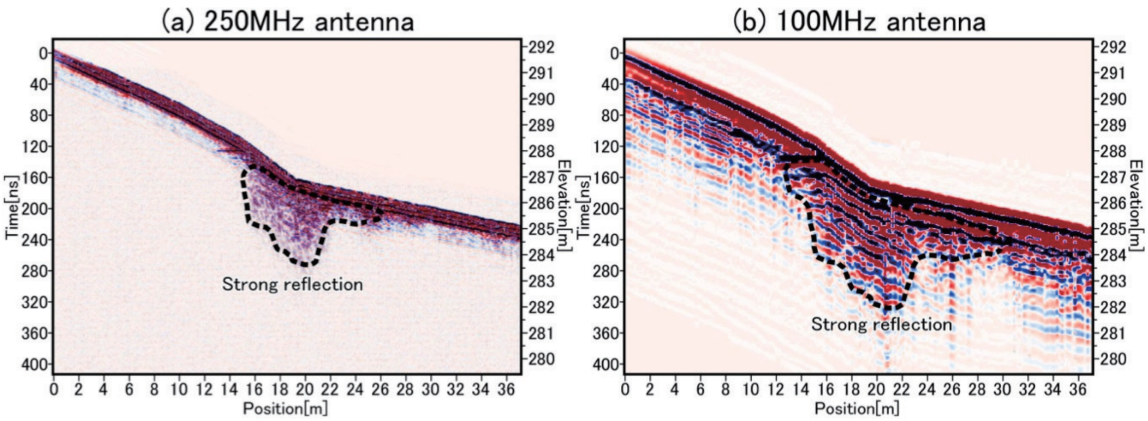

Fig. 10. GPR survey profiles in 2011: (a) 250 MHz antenna, (b) 100 MHz antenna

(2) GPR survey in November 2012

In October 2012, about a year after the survey conducted in August 2011, workers (from Niigata Prefecture) who were restoring the landslide area discovered that water at a temperature of 0°C was flowing away from a drainage hole. The sediment near the drainage hole was excavated (Fig. 11), and a 1-m thick snowpack was discovered at a depth of 4.2m below ground. The snowpack had similar hardness to ice with the compression.

Fig. 11. The excavation site showing a snowpack in the landslide sediment.

We conducted a GPR survey in the area where the snowpack was found. A survey line length of 40m was set and antennas with a center frequency of 250MHz (Noggin plus) and 100MHz (pulse EKKO Pro) were used. Figure 12 shows a photograph of the survey in November 2012 and elevation of the survey line. The survey results were analyzed using a radar velocity of 0.05m/ns, estimated from a CMP survey. During the survey, the temperature of the water flowing from the drainage hole was about 5°C, suggesting that the snowpack had been melting gradually.

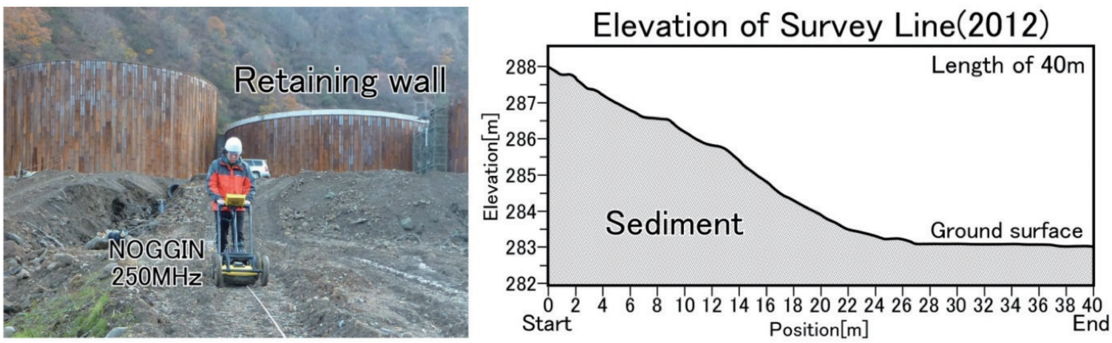

Fig. 12. Photograph of survey in November 2012 and elevation of the survey line.

Figure 13 shows the representative GPR profiles obtained from the 250MHz antenna (Fig. 13 (a)) and the 100MHz antenna (Fig. 13 (b)). In both the profiles, there were multiple reflections at distances of 28-30m and 34m from the survey starting point. These reflections may be caused by puddles of rainwater on the ground surface. In the profile shown in Fig. 13(b), another reflection anomaly was identified at a distance of 22m from the survey starting point, at a depth of 2.5-3m. As these reflection patterns were thought not to be rocks and soil strata, and the snowpack in the ground was identified as strong reflections by the experiment, this was possibly a response from the remaining snowpack in the sediment.

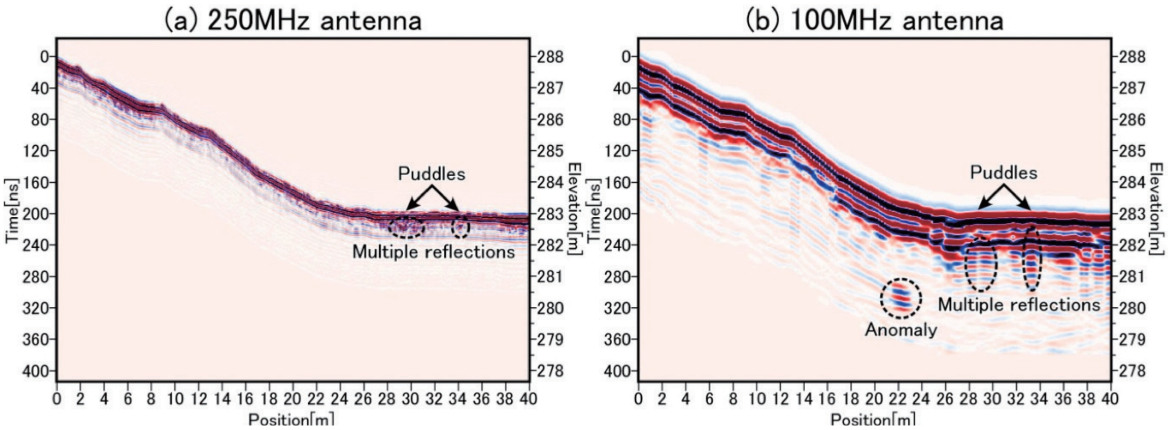

Fig. 13. GPR profiles of the 2012 survey: (a) 250MHz antenna, (b) 100MHz antenna

5. Discussion

We applied the results of our experimental field surveys of artificially buried ice and snow to interpret the GPR survey data of the landslide area at Tatsunokuchi. Strong reflections were observed at three locations in the 2011 survey (Fig. 14 (a)). All anomalies extended vertically to depths of a few meters, similar to the multiple reflections caused by the meltwater of snow and ice in the experimental survey. The results of the 2011 survey therefore indicated that water contained in snowpack was distributed inhomogeneously.

Multiple reflections observed from puddles on the ground were similar to the experimental results (Fig. 14 (b)). The strong reflection at distances of 21-23m from the survey starting point, at a depth of 2.5-3.5m, was likely the response of the remaining subsurface snow.

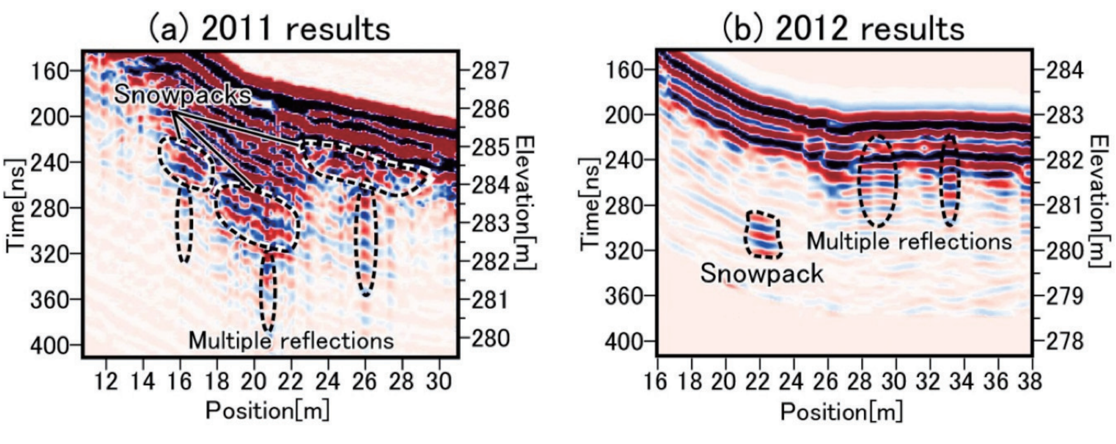

Fig. 14. GPR profiles at 100MHz. (a) 2011 results, (b) 2012 results. The black dashed lines show snow packs and multiple reflections. The results were examined by the reflection's pattern gained by the experiment, and are the enlarged area.

The velocity of radar waves in the landslide sediment was 0.05-0.06m/ns, which is slower than typical velocities through the ground, indicating that the sediment was rich in moisture (Society of Exploration Geophysicists, 1998). The radar waves were sharply attenuated at a depth of 1.5m by increased moisture underground. However, the compressed snowpack caused a strong anomaly, resulting in the identification of a snowpack area.

The results showed that entrained snow in the landslide sediment could remain for more than one year, indicating that there is a potential risk of a secondary landslide due to meltwater from persistent snow in the sediment.

The average annual temperature in Tsunan-machi is 10.5°C and temperatures have occasionally reached over 34°C during 2011 and 2012, according to the Japan Meteorological Agency. Snowpacks have remained in the landslide sediment for more than a year despite these temperature ranges. Possible causes of the subsurface area being less affected by temperatures above ground are the heat insulation effect by rich moisture of the sediment, and the snow stable at a temperature of 0°C being insulated by air remaining in the compressed snow.

6. Conclusions

A landslide was triggered by the North Nagano Prefecture earthquake in the Tatsunokuchi area of Tsunan-machi in Niigata Prefecture and the main mass entrained the snow in the area. The results of GPR surveys in the area indicated that the snowpacks can remain in the landslide sediment for more than a year, which was visually confirmed by the excavation. In the controlled field experiments, where snow and ice were artificially buried in the subsurface, strong reflections observed from the landslide sediment were likely caused by the response of a snowpack, and the vertical extension of the reflection was the result of multiple reflections by meltwater.

The GPR surveys identified clear reflection patterns caused by subsurface snow and ice and therefore allowed the area of entrained snow in the landslide sediment to be determined. Such snow could remain in the sediment for more than one year, creating a potential risk for a secondary hazard by the looseness of the ground (Ito, 2003). The GPR survey is a highly effective method of investigating such areas and monitoring changes. In future work, efficient GPR methods in areas with debris should be developed to conduct effective surveys of landslides. Furthermore, measurements of the electromagnetic properties of soil mixed with snow would help estimate the amount of snow buried in the landslide sediment.

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