ACCELERATION PROCESSES OF SNOW GLIDE PRIOR TO FULL-DEPTH AVALANCHE RELEASE ON SHRUB SLOPES IN THE TEMPERATE HEAVY-SNOW REGION OF JAPAN

Katsuhisa Kawashima[1]*, Tsutomu Iyobe[2] and Takane Matsumoto[1]

[1]Research Institute for Natural Hazards and Disaster Recovery, Niigata University, Niigata, Japan
[2]Graduate School of Engineering, Kyoto University, Kyoto, Japan

ABSTRACT: In the temperate heavy-snow region of Japan, most of snow avalanche disaster arise as a consequence of the full-depth glide avalanche in the area with human activities. Although snow glide motion of a snow cover on slope is one of the most important factors for full-depth avalanche release, snow glide acceleration processes are still poorly understood, which disturbs improvement of the prediction accuracy. In this study, we were intended to contribute to the accumulation of snow glide data prior to full-depth avalanche release on the shrubby slopes. Measurements of snow glide by glide shoes were made on two slopes covered with deciduous shrubs (3–10 m in height), which is typical vegetation on avalanche-prone slope in Niigata Prefecture, central Japan. Consequently, we observed 3 full-depth avalanche events. Our data showed that snow gliding shifts its motion. It starts with "uniform motion", continues with "constant acceleration motion", then "increasing acceleration motion". The last stage is the most important for avalanche forecasting, because this brings about avalanche release. Further analysis of increasing acceleration stage, it became clear that glide acceleration rate is an increasing function of glide rate and is directly proportional to the square of glide rate. This relation provides a convenient method for estimating the time to avalanche release for snow slab with given glide rate, which seems likely to be applicable to the short-time forecast of full-depth glide avalanches in the future.

KEYWORDS: full-depth glide avalanche, snow glide, avalanche release, shrub slope

1. INTRODUCTION

Since snow glide motion of a snow cover on slope is one of the most important factors for full-depth glide avalanche release, measurements of snow glide have been made in Switzerland, Austria, Italy, North America and Japan up to now at various avalanche-prone slopes by using glide shoes. Ground surface roughness, terrain shape and snow characteristics have significant effects on snow gliding and the resultant formation of cracks and avalanches (in der Grand and Zupancic, 1966).

As for the vegetation-related surface roughness, field measurements showed that grassy slopes and impermeable rock beds devoid of vegetation are prone to active gliding (e.g., in der Grand and Zupancic, 1966; McClung et al., 1994; Stimberis and Rubin, 2011). On the other hand, Endo (1984) reported that bamboo bushes can have an anchoring effect against snow gliding when their stalks and leaves are kept in the snow cover without falling down. Höller (2001, 2014) investigated snow gliding on a slope covered with larch trees to reveal that snow gliding is strongly influenced by the canopy density; consequently the author specified the number of stems required to prevent high glide rates. It has been pointed out that snow gliding is affected by topography of the slope: in particular slope inclination and aspect (e.g., in der Grand and Zupancic, 1966; Lackinger, 1987). Clarke and McClung (1999) described a slope greater than 15° for roughness typical of alpine terrain as one of the prerequisites for the onset of gliding. Most glide-snow avalanches occur on 30–40° steep slopes and release on convex rolls (Schweizer et al., 2015). Snow characteristics is believed to be a crucial factor exerting a decisive influence on the stability and timing of glide avalanches release. Field observations showed that snow gliding generally occur under the presence of a well-settled wet-snow layer at the base of snow cover (McClung, 1975). It is widely acceptable that the existence of liquid water at the snow-ground interface reduces the friction between snow and ground as well as the strength of snow (McClung and Schaerer, 2006). For this reason, precise estimate of water flux reaching the snow-ground interface may help to the prediction of glide-snow

* *Corresponding author address:*
Katsuhisa Kawashima, Research Institute for Natural Hazards and Disaster Recovery, Niigata University, Ikarashi-Ninocho 8050, Nishi-ku, Niigata 250-2181 Japan;
tel: +81-25-262-7056; fax: +81-25-262-7050;
email: kawasima@cc.niigata-u.ac.jp

avalanches. Recently, Mitterer and Schweizer (2012) demonstrated the formation of a wet basal layer by capillary rise due to different hydraulic pressures along the snow-soil interface, indicating the importance of revealing hydraulic interaction between snow and ground.

Over the past half a century or more, a considerable number of studies have been conducted on the snow gliding and glide-snow avalanche formation, as reviewed by Höller (2014) and Ancey and Bain (2015). However, the whole picture of them is not completely clarified since there exists many relevant parameters: topography, vegetation, soil and ground surface conditions, meteorological conditions and so on. The prediction of glide-snow avalanche release requires not only an understanding of quantitative relationships between gliding and relevant parameters but also more field knowledge about acceleration processes of gliding, both of which may lead to the improvement of modeling of snow gliding.

In this study we present data of snow gliding measured on avalanche-prone slopes dominated by deciduous broad-leaved trees in the temperate heavy-snow region of Japan. So far little is known about characteristics of time variation in glide rate on slopes covered with above-mentioned vegetation and heavy snow cover, in spite of many victims, damages to infrastructures and traffic and transport disturbances by glide-snow avalanches in this area (Izumi et al., 1997). Special attention is given to snow glide acceleration processes prior to full-depth glide avalanche release to verify the applicability of a time-dependent model of basal resistance force, proposed by Nohguchi (1989).

2. METHODS

2.1 <u>Study sites</u>

We have two sites for snow glide observations in Niigata Prefecture, central Japan as shown in Figure 1: Oshirakawa site (400 m a.s.l.) and Ojiya site (150 m a.s.l.). The former has a northwest aspect and an average slope inclination of 38° (Figure 2(a)), and the latter has a southeast aspect and an average slope inclination of 40° (Figure 2(b)). The winter mean air temperature (December–February) and average annual maximum snow depth are -0.8°C and 2.7 m, respectively at Oshirakawa site, whereas 0.6°C and 1.8 m at Ojiya site (Japan Meteorological Agency, 2012). At both sites, the vegetation is dominated by deciduous broad-leaved trees (3–10 m in height) with the flexible stems. The main species are *Alnus*, *Deutzia* and *Acer*. In winter all stems are affected by snow pressure to fall down flat on the slope. Therefore, the snowpack may slip downhill on the slope surface covered with procumbent stems (Figure 3).

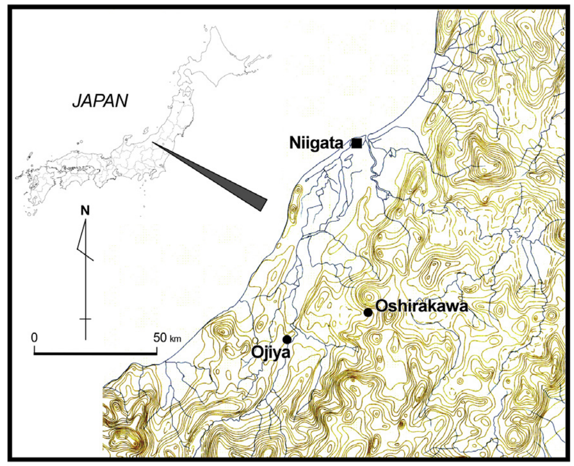

Fig. 1: Map of two study sites (closed circles) in Niigata Prefecture, central Japan.

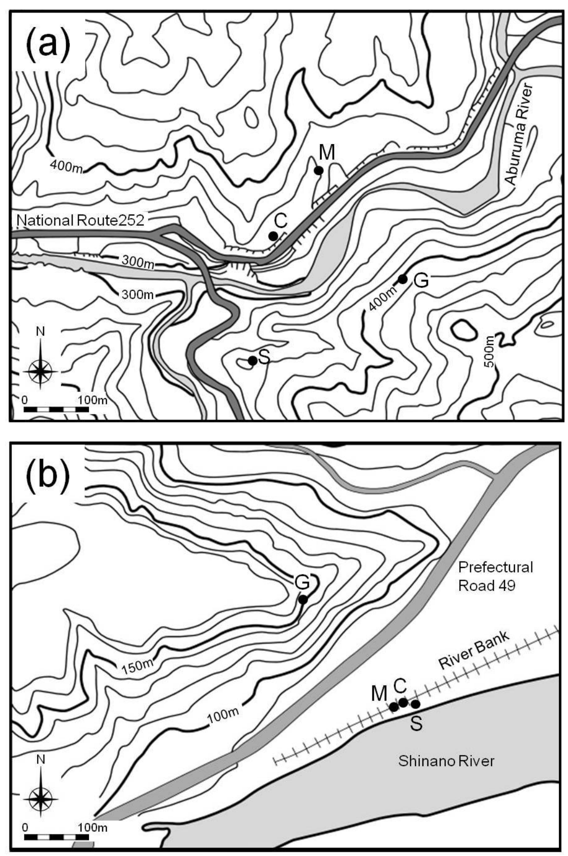

Fig. 2: Topographical map of Oshirakawa site (a) and Ojiya site (b). G: glide shoe, M: automatic weather station, S: snow pit, C: camera.

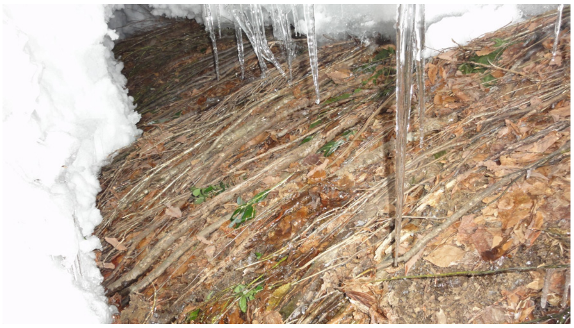

Fig. 3: Photograph of ground surface in a glide crack on 14 February 2014 at Oshirakawa site. The snow cover is about 2.4 m in height. Field evidence of snow gliding on procumbent stems.

2.2 Measurement of snow glide

Measurements of snow glide were made using snow-glide instrumentation (shoe type glide-meter) originally developed by in der Grand and Zupancic (1966). Stainless-steel glide shoes (0.4 m in length and 0.3 m in width) were placed on the starting zones of each site (points G in Figure 2) and fastened to cable extension transducers with steal wires. When shoes move with the snow glide, downslope displacement of shoes can be measured by the transducers in 10 minutes intervals and transmitted to our laboratory in real-time by cellular phones. The measuring range and resolution of snow glide are 0–15 m and 1.5 mm, respectively in this total measurement system.

2.3 Meteorological and snow pit observations

At both sites, meteorological observations were conducted at points M in Figure 2. Meteorological observations by automatic weather stations (AWS) includes snow depth, precipitation, air temperature, relative humidity, wind speed and direction, shortwave radiation (incoming and outgoing) and longwave radiation (incoming and outgoing). A pressure-sensing snow pillow for measuring the snow water equivalent and a device detecting temperature of newly fallen snow were installed only at Oshirakawa site. The latter, originally developed by Tamura (1992), permits a fairly-precise discrimination of the precipitation type (rain or snow). All sensors were connected to data loggers and measured data were recorded in 10 minutes intervals. Observations of snow stratigraphy, snow type, snow temperature, snow density and liquid-water content were made several times a month by the snow pit method on slopes (points S) whose aspects are approximately the same as the starting zones of each site. In addition, a web camera (Oshirakawa site) and a time-lapse camera (Ojiya site) were installed at points C to monitor the formation of glide cracks and glide-snow avalanches.

3. RESULTS

Field measurements have been made since the snow season of 2012/13 at both sites. Consequently, we successfully obtained data of snow glide before three full-depth glide avalanches: one event at Oshirakawa site on 6 February 2015 and two events at Ojiya site on 17 December 2012 and 16 January 2013. In this paper, we mainly highlight the avalanche event at Oshirakawa site and discuss snow glide acceleration processes prior to full-depth glide avalanche release.

3.1 Weather conditions during the snow season of 2014/15

The snow season of 2014/15 was characterized by frequent heavy snowfall events in early winter (December–January) and repeated snowmelts (rises in air temperature above 0°C) and rain-on-snow events throughout the season (Figure 4). The period of snow cover was from December 5 to May 8. The maximum snow depth was 3.93 m on 14 March, while the snow water equivalent reached a maximum (1946 mm) on 19 March.

A glide snow avalanche occurred at 9:26 on 6 February. Over the previous 2 days, it was fine weather with no precipitation, thereby increasing air temperature in the daytime up to 4.6°C on 4 February and 7.4°C on 5 February. Contrary to this, on the day of the avalanche release, the northwesterly monsoon brought the slightly lower temperature and additional snow to the Oshirakawa site. These weather conditions suggest that both the decrease in the resistance force at the snow-ground interface due to snowmelt and the increase in the driving force due to additional load possibly triggered the avalanche release.

3.2 Snow conditions until the avalanche event

Stratigraphies, grain shapes and liquid-water content of snow observed at Oshirakawa site on 12 January, 28 January and 6 February are shown in Figure 5. The liquid-water content, measured by the dielectric method (Denoth, 1994), is expressed by terms specified in the international classification (Fierz et al., 2009). Reflecting the repeated snowmelts and rain-on-snow events, the snow has already metamorphosed into rounded grains (melt forms) in the moist or wet state even in January except for the surface layers. On the day of the avalanche release, the mean density of entire

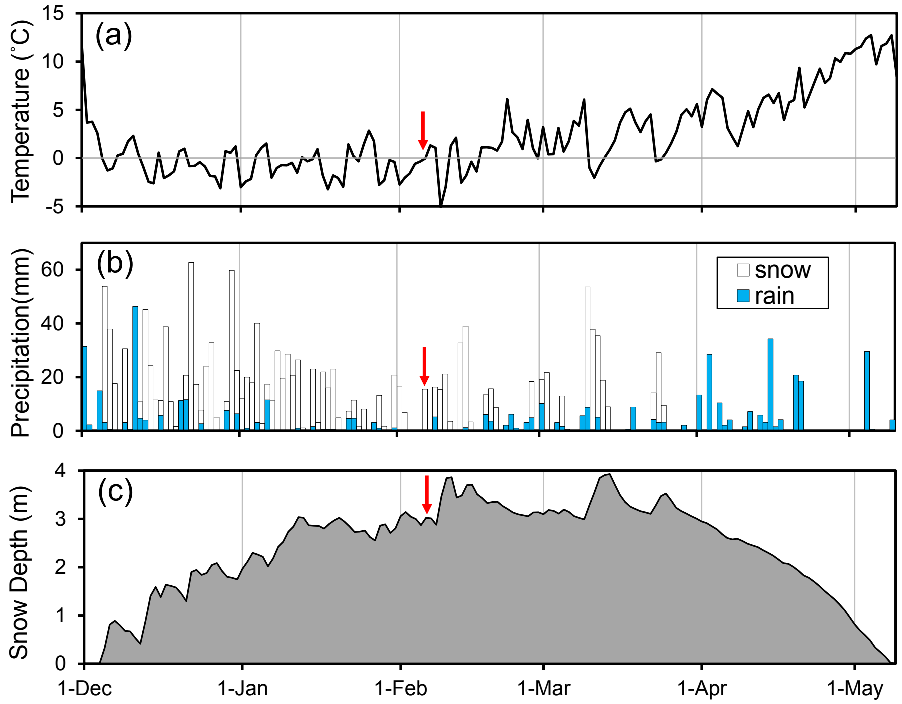

Fig. 4: Daily mean air temperature (a), daily precipitation (b) and daily maximum snow depth (c) observed at Oshirakawa site during snow season of 2014/15. Daily precipitation is discriminated between snow and rain. The arrows show the date of glide-snow avalanche release.

snow cover was 350 kgm^{-3}. The density of basal snow layer reached 500 kgm^{-3}, although water-saturated snow layers, such as those shown by Mitterer and Schweizer (2012), were not found at the bottom of snow cover.

3.3 Avalanche event at Oshirakawa site on 6 February 2015

Sequence of images of the targeted slope, taken with the web camera, are shown in Figure 6. Glide cracks immediately beneath the ridge line and longitudinal cracks at both sides of snow slab were recognized before the avalanche release (Figure 6(a)). The break-up of the snow slab occurred to start a flowing avalanche 10 seconds after release (Figure 6(b)). The avalanche was almost completed in 50 seconds after release (Figure 6(c)). As the result of a survey of the starting zone made on the afternoon of 6 February, it was found that this avalanche involve about 13000 m^3 of snow, equivalent to a mass of 4550 tons in light of the mean snow density of 350 kgm^{-3}. The starting zone after release was characterized by shrubs restored to their original state by being freed from snow pressure (Figure 7). Overturned snow blocks stopping at the uppermost part of the track without reaching the runout zone made it possible to observe the

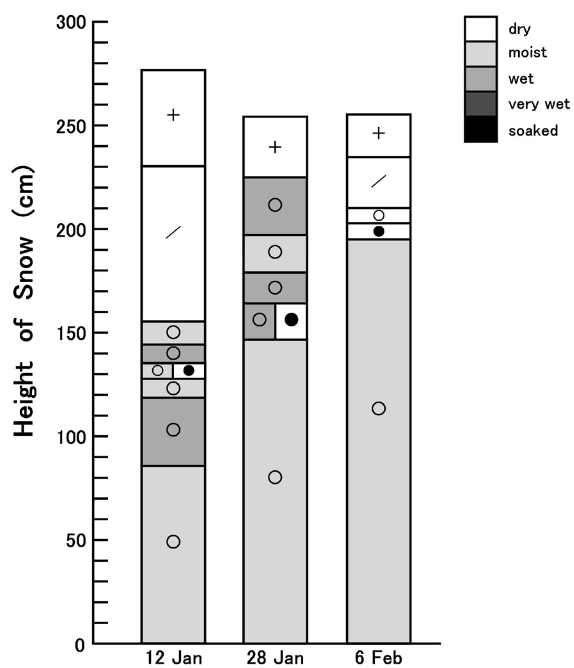

Fig. 5: Stratigraphies, grain shapes and liquid-water content of snow cover observed at Oshirakawa site (points S in Figure 2(a)) in 2015. The classification of grain shape, symbols and terms are referred to Fierz et al. (2009).

basal snow layer (Figure 8). Consequently, remarkably hard and wet snow layer with thickness of 1–2 cm was found at the bottom of snow cover. The dry density of this layer was estimated to be much higher than the maximum snow density due to mechanical packing (approximately 550 kgm^{-3}). This high-density layer may be formed by the densification in the presence of liquid water, because it makes no sense at all that cold wave can penetrate deep into the isothermal snow cover.

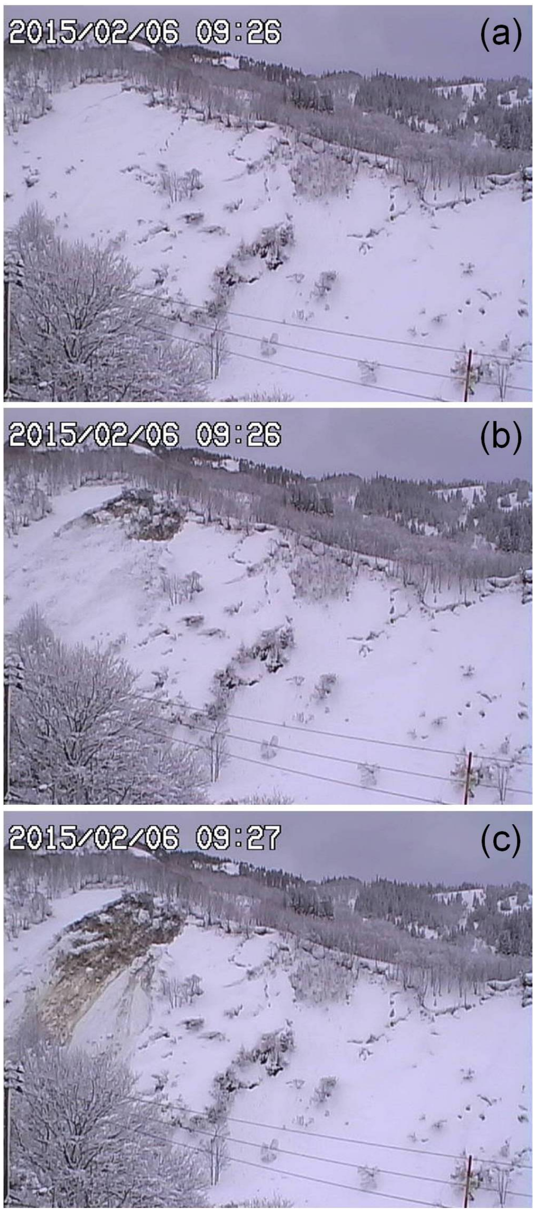

Fig. 6: Sequence of images showing changes of the targeted slope: (a) 1 second before avalanche release, (b) 10 seconds after release (flowing avalanche) and (c) 50 seconds after release (completion of avalanche).

Fig. 7: View of the starting zone at 14:39 on 6 February after 5 hours of avalanche release.

Fig. 8: Photograph of the bottom of snow cover (overturned snow block).

3.4 Snow glide rates

A shoe type glide-meter came into operation on 16 December 2014. Changes in snow glide and glide rate with time from December 16 to February 6 are shown in Figure 9. The glide rate was calculated from snow glide at intervals of 10 minutes. One of the major features of the glide rate is a monotonically increasing curve without jerky behaviors. The glide-snow avalanche occurred at 9:26 on 6 February immediately after the glide rate reached 413 mm/h at 9:20. From December to the end of January, the snow glide increased in a linear manner, indicating the uniform motion. Actually, during above period, the glide rate maintained almost constant value of 1–2 mm/h. On the other hand, after the end of January, the snow glide rapidly increased to result in avalanche release on 6 February. These data mean that snow gliding shift around January 29 from uniform motion to

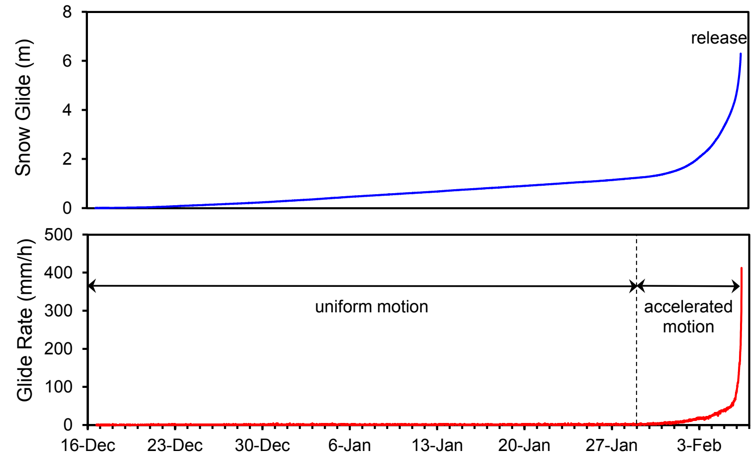

Fig. 9: Changes in snow glide and glide rate with time from 16 December 2014 to 6 February 2015 at Oshirakawa site.

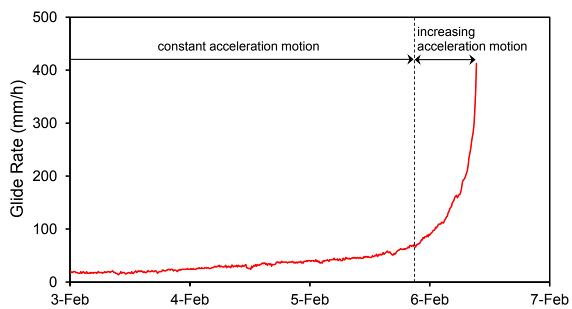

Fig. 10: Change in glide rate with time during 3–6 February 2015 at Oshirakawa site.

accelerated motion. In order to examine the accelerated motion stage in more detail, change in glide rate for 4 days before avalanche release is shown in Figure 10. Until the evening of February 5, the glide rate increased in a linear manner, indicating the constant acceleration motion. While, the glide rate rose sharply from 21:00 on 5 February, showing that snow gliding shift its motion from constant acceleration to increasing acceleration.

4. DISCUSSION

The measurement of snow glide at Oshirakawa site revealed that snow gliding consists of three stages. The last stage, namely increasing acceleration motion, is the most important, because this leads directly to avalanche release. Therefore, focusing on the last stage, we proceed to a discussion about how the increasing acceleration motion can be treated quantitatively.

A mathematical model for instability in snow gliding motion, proposed by Nohguchi (1989), provides a useful clue about this. Nohguchi (1989) derived the following simple equation as an approximate expression in case of acceleration process of glide prior to avalanche release:

$$\frac{dv}{dt} = av^2, \qquad (1)$$

where v is glide rate, t is the time, and a is the parameter relating to the degree to which the real contact area between snow and ground decreases during gliding. The left side of the equation represents the glide acceleration rate. If our field data can be matched with Equation (1), it will become possible to consider the last stage quantitatively. The glide acceleration rate during the last stage was calculated at intervals of 10 minutes and plotted against glide rate in Figure 11. As a result, it became clear that field data at Oshirakawa site fit well with Equation (1). The value of parameter a was estimated to be 0.0008 mm^{-1} by the method of least squares. The same analysis confirmed that Equation (1) is also well-suited for two avalanche events at Ojiya site on 17 December 2012 and 16 January 2013. Comparing three fitted curves in Figure 11, the glide acceleration rate at Ojiya site is slightly larger than that at Oshirakawa site under a given glide rate. This difference is expressed in differences in the parameter a. The parameter a lies in the range of 0.0008–0.0012 mm^{-1} for the three avalanche events.

Equation (1) provides a convenient method for estimating the time to avalanche release for snow slab with glide rate v_0. The time T is given by

$$\mathrm{T} = \frac{1}{av_0}. \qquad (2)$$

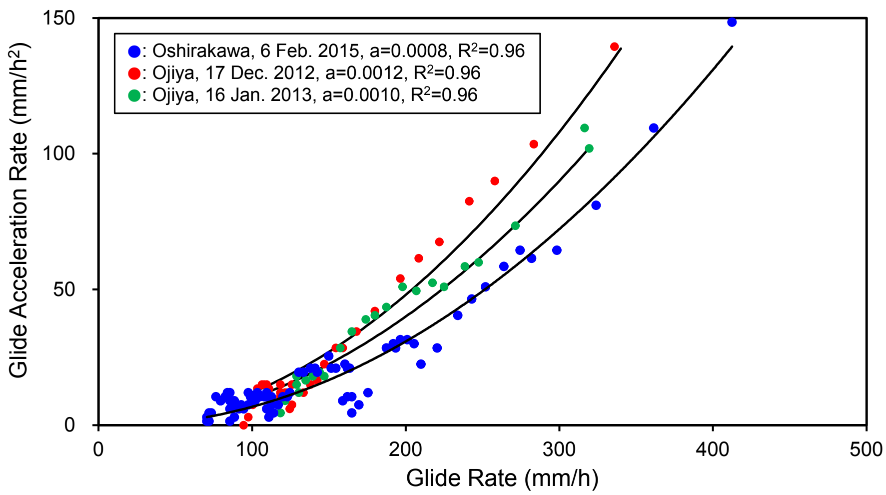

Fig. 11: Relation between glide rate and glide acceleration rate. Solid lines are fitted curves. R^2 is the coefficient of determination.

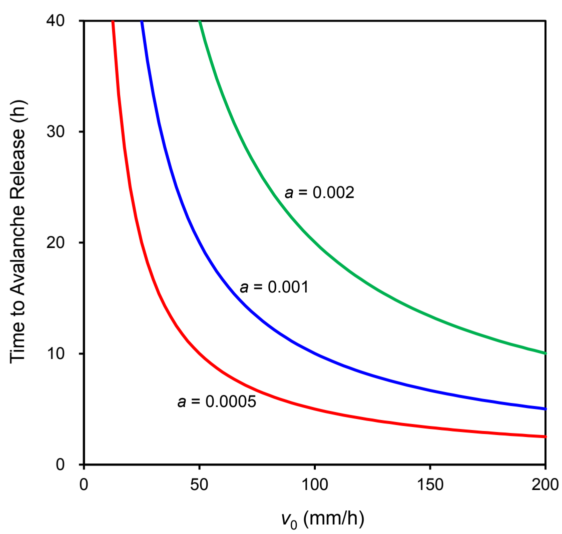

Fig. 12: Relation between glide rate v_0 and time to avalanche release for various values of parameter *a*.

The time *T* calculated using Equation (2) is shown in Figure 12 as a function of v_0. In this calculation, we employed three values (0.0005, 0.001 and 0.002 mm^{-1}) of parameter *a*. The value of 0.001 is an average one which we obtained in this study. Other two are its half and double values. If the range of parameter *a* is proper for shrub slopes, we have 5-20 hours to escape when the glide rate is 100 mm/h.

As seen above, this simple method for estimating the time to avalanche release seems likely to be applicable to the short-time forecast of full-depth glide avalanches in the future. For this purpose, however, there remains challenges as follows.

(1) When and why does the snow gliding shift its motion? What is the trigger mechanism?

(2) How can we know the present stage of snow gliding motion? Especially, now is the “increasing acceleration motion” or not.

(3) How can we determine the parameter *a*? It links glide acceleration rate with glide rate, and is sure to differ depending on vegetation-related surface roughness, terrain shape, snow property and so on.

5. CONCLUSIONS

In order to contribute to the understandings of acceleration processes of snow gliding, measurements of snow glide by glide shoes were made on two slopes covered with deciduous shrubs (3–10 m in height), which is typical vegetation on avalanche-prone slope in Niigata Prefecture, central Japan. Consequently, data of snow glide before three full-depth glide avalanches were obtained. Focusing on the avalanche event at Oshirakawa site on 6 February 2015, we showed snow glide acceleration processes prior to glide avalanche release as well as snow conditions and avalanche characteristics. Our data showed that snow gliding shifts its motion. It starts with “uniform motion”, continues with “constant acceleration motion”, then “increasing acceleration motion”. The last stage is the most important for avalanche forecasting. During the last stage, the glide acceleration rate was confirmed to be directly proportional to the square of glide rate, which is the same result indicated by Nohguchi (1989). This relation provides a convenient method for estimating the time to avalanche release for snow slab with given glide rate, which seems likely to be applicable to the short-time forecast of full-depth glide avalanches in the future.

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