MEASURING THE RESISTIVE FORCE OF SHRUBS ACTING ON A GLIDING SNOW SLAB

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ABSTRACT: A glide-snow avalanche is triggered by snow gliding at the interface between the snow and the ground. The roughness of the ground, the presence of vegetation, and the existence of liquid water influence the friction on the ground. Shrubs and small tree are typical vegetation in avalanche-starting zones in Japan that support the snow slabs and reduce gliding. Understanding the magnitude and variations in the resistive force of vegetation is crucial for forecasting glide-snow avalanches on slopes with vegetation cover, designing technical avalanche protection measures, managing avalanche protection forests in avalanche-starting areas. Using strain gauges, we measured the tensile strain on the trunks of small tree which has a shrub like shape trunk buried in the snow slab in the avalanche-starting zone. We determined the resistive force exerted by the small tree on the snow slab until just before the release of the avalanche. We conducted measurements on two small trees of different sizes over two snow seasons. The measurements showed that larger tree exerted a larger resistive force. The maximum resistive force values appeared at the earlier of the snow season, after which the resistive force gradually decreased. The maximum values for each tree remained similar in the two winter seasons. However, the timing of the appearance of these maximum values and their subsequent decrease varied for each tree and year. In years when the maximum force appeared late, the release of the glide-snow avalanche also occurred late. Deformation of the trunk due to snow loads and wet metamorphism of the snow layer where the tree is buried may decrease the resistive force of the tree.

KEYWORDS: glide-snow avalanche, vegetation, resistive force, strain gauge, protection forests

1. INTRODUCTION

A snow gliding, a slow movement of the snowpack on the slope, triggers a glide-snow avalanche. Snow gliding is influenced by various factors such as slope angle, surface roughness, vegetation, and the wetness of the snow layer near the ground (in der Gand and Zupančič, 1965). When the snowpack in the starting zone starts to glide, cracks form due to tensile stress in the upper part of the starting zone. Following this, compressive stress increases in the lower part of it, called stauchwall. It can lead to avalanches when the compressive stress causes the failure of the stauchwall (Lackinger, 1987; Batelt et al., 2012). Most glide-snow avalanches are released either without any prior glide crack formations or within 24 hours after crack formations (Fees et al., 2023). However, some have been observed to occur several days later (Lackinger, 1987). The glide velocities increase before avalanche release (Akitaya, 1976; Stimberis and Charles, 2011; Fees et al., 2023). This may be due to reduced friction at the ground-snow interface, either due to the existence of free water at such interface (McClund and Clarke, 1987) or to a reduced contact area between the ground and the snow (Nohguchi, 1989). Understanding how glide avalanches are released is essential for avalanche forecasting, designing technical avalanche protection measures, and managing avalanche protection forests. However, our understanding of how friction at the ground-snow interface and compressive failure of stauchwall is partly inadequate.

The vegetation in starting zones affects glide progression and glide-snow avalanche formation. Previous studies suggest that the effect of vegetation on these processes depends on the type, size, and density of the vegetation. Tall trees can reduce glides by acting as anchors with their trunks. Glide-snow avalanches can occur in open forests, with the glide distance and the glide speed greater in areas with fewer trunks per unit area (Ishikawa et al., 1969; Aiura, 2005; Leitinger et al., 2008; Höller, 2014). Additionally, it has been observed that low trees or large shrubs can limit the glide distance, while lower, soft dwarf shrubs have less of an inhibitory effect (Newesely

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et al., 2000). To address this effect of vegetation on snow gliding in physical models to assess the release of glide-snow avalanches, Coulomb's friction coefficients, including the effect of vegetation, have been defined based on the vegetation type and ground surface roughness (Feistl et al., 2014).

Several studies have indicated that the effect of vegetation on glide changes over time. For instance, standing bamboo within the snowpack initially acts as a resistive force to snow gliding. However, as the snow gliding starts, the bamboo gradually slips out from the inside of the snowpack, reducing the resistive force (Endo, 1983). The load of the snowpack compresses vegetation, such as grass and shrubs. Increased snow depth further compresses the vegetation, decreasing surface roughness and friction due to the vegetation (Yamanoi, 2006; Feistl et al., 2014). This effect is linked to the mechanical properties of vegetation for the snowpack load. These suggest the importance of considering temporal changes in the resistive force of vegetation when predicting snow glide avalanche release. Nevertheless, direct measurements are lacking, and further clarification is needed.

This study aims to determine the resistive force of vegetation to snow gliding. It focuses on low trees, typically found in avalanche-starting zones at snowy and relatively low altitudes area in Japan. The study attempts to directly measure the resistive force to snow gliding by using strain gauges attached to the trunks of the tree. Continuous strain measurements show how the resistive force changes from the start of snow accumulation to the release of the glide-snow avalanche. The study also discusses the factors that cause the change in resistive force.

2. METHODS

2.1 Study site

The study site is the Oshirakawa site (400 m a.s.l.; 37° 20.4N, 139° 7.8E) in Uonuma, Niigata Prefecture, Central Japan. Glide-snow avalanches occur frequently at this site, although not every winter. This site has also been used for various studies, including the acceleration of glide speeds (Kawashima et al., 2016) and bending strain measurements on tree trunks in the starting zone (Miyashita et al., 2018). The mean incline of the starting zone is approximately 38°, and the slope faces northwest. Tall trees are absent in the starting zone, and small tree species of *Acer spp.* and shrub of *Hamamelis japonica* are predominantly growing. *Quercus crispula* and *Fagus crenata* are partially grown. None of the trees grow upright; almost all tree trunks are significantly curved and these have a shrub like shape. The trunks near the ground are almost parallel to the ground due to past snow loads. Most parts of the forest floor were covered with litter, and there were smooth rocks in a few steep positions.

2.2 Measurements

The study involved measuring the strains on the trunks of small trees that were growing in the starting zone until a snow avalanche occurred. The measurements were taken during the winters of 2021-22 and 2022-23. Two small trees of *Acer spp.* growing in different locations in the same starting zone were selected for measurement. The trunk diameters near the ground were 17.4 cm for tree A and 6.2 cm for tree B, respectively. Tree A is close to the largest size of the trees, and tree B is a typical size of the tree growing in this starting zone.

The measured strain was used to determine each tree's resistive force to snow gliding. The trunk bents due to snow accumulation on their canopies. As the snow depth increases, the tree becomes buried in the snowpack. The snow settlement, snow gliding, and snow melting at the bottom of the snowpack cause causes further bending of the trunk. Eventually, the trunk becomes almost parallel to the ground. During this time, the trunk experiences bending stress from the snow load and tensile stress from resistive force to snow gliding. Additionally, there is horizontal bending stress in the trunk when it is misaligned with the direction of snow gliding. We must isolate only the tensile stresses among these three different stress components to determine a tree's resistive forces. In this study, we measured the strains on both sides of the trunk, corresponding to the neutral axis of the bending stress caused by the snow load, to minimize the effects of bending stress. The measured strains were converted to stress using Young's modulus, which we measured on-site. We canceled out the horizontal bending stress of the trunk by adding the measured stress on both sides.

We used strain gages with five elements arranged in parallel at 2 mm intervals on a gauge sheet (Tokyo Measuring Instruments Laboratory Co., Ltd., FYV-1-11-002LE) (Fig. 1). The strain gauges were attached to the xylem of the trunk near the ground with Cyanoacrylate adhesive (Tokyo Measuring Instruments Laboratory Co., Ltd., CN-E). The bark of the trunks at the attaching positions was peeled off with a chisel to expose the xylem and smooth it out. We wrapped Butyl rubber-type tapes (Tokyo Measuring Instruments Laboratory Co., Ltd., SB tape, VM tape) and duct tapes (Gorilla Glue, Inc., Silver Gorilla Tape) around the gauges to protect them. After attaching the gauges, we hung weights on the trunk tip to generate artificial bending stress and measured the change in strain in each strain gauge element. The exact position of the neutral axis and the two strain gauges adjacent to the neutral axis were determined from the change in the measured strain. We continuously measured strains by two strain gauges close to the neutral axis throughout the winter. These measurements were taken on both sides of the trunks of two small trees. A network measurement system was used to measure the recording unit placed at different

Figure 1: Strain gauges attached on the trunk of tree A.

locations and connected by cables. The measurement units (Tokyo Measuring Instruments Laboratory Co., Ltd., NSW-024C) were placed on the ground near the base of each tree, and the recording unit (Tokyo Measuring Instruments Laboratory Co., Ltd., MD-111) was placed on the ridge at the top of release zone at this site.

2.3 Snow profile simulation

We conducted a snow profile simulation to discuss how snow profiles affect changes in resistive force over time. The simulation used a snow model that implement the water infiltration model (Katsushima et al., 2009; Ikeda et al., 2014). This model takes into account the influence of capillary barrier and non-uniform water infiltration caused by preferential flow paths. We used weather data from an Automatic Weather Station (AWS) located in a flat space opposite the study slope as input for the model.

3. RESULTS

3.1 Resistive force of small tree

Figure 2 shows the temporal change of the resistive force of trees A and B during the winters of 2021/22 and 2022/23. On the study slopes, glide avalanches occurred on 14 April in the winter of 2021-22 and on 3 February in the winter of 2022-23. The measured resistive force tended to increase after the snow had accumulated on the ground and to decrease after the maximum value had appeared. In the winter of 2021-22, resistive force started to increase on 4 January for tree A and 28 December for tree B; in 2022-23, it started on 18 December for tree A and 15 December for tree B. In both winters, the timing when resistive force started to increase for tree A was later than for tree B. The decrease in resistive force was not constant concerning time but rather repeated small in increases and decreases. A significant temporary increase was observed before the onset of the avalanche in 2022/23 for tree A and 2021/22 for tree B.

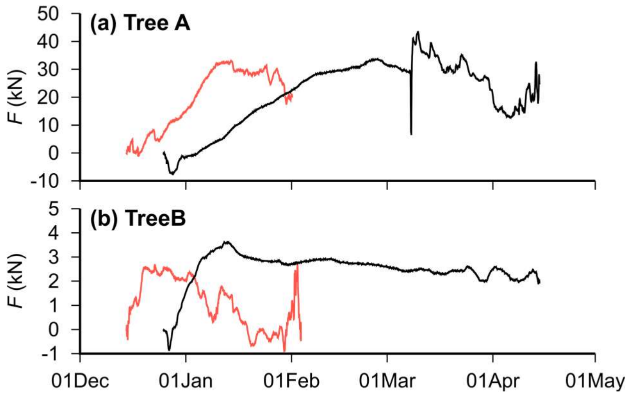

Figure 2: Temporal change of the resistive force of (a) tree A and (b) tree B during the winters of 2021/22 (Black line) and 2022/23 (Red line).

In the winter of 2021-22, the resistive force for tree A experienced a sudden increase of about 12 kN on 8 March, which remained at this heightened level thereafter. This behavior may have been caused by issues with the measuring instrument. We then assumed that the maximum resistive force before this increase occurred is the maximum value for that winter. The maximum measured resistive force was 33.5kN on 26 February for tree A and 3.6kN on 12 January for tree B in winter 2021-22 and 30.9kN on 14 January for tree A and 2.7kN on 22 December for tree B in winter 2022-23, respectively. The maximum resistive force appeared earlier in the snow season, such as in December and January, and it was similar between winters in both trees. However, the timing of their appearance differed significantly depending on the winter. The measured resistive force before the avalanche was approximately 20 kN for tree A in both winters. For tree B, it was approximately 2 kN in 2021-22, but in 2022-23, it decreased to around 0 N two weeks before the avalanche.

3.2 Snow profile simulation

Figure 3 shows the temporal change of the vertical profile of volumetric water content as simulated by the snowpack model. Initially, most of the snow layer was dry snow, but as water from subsequent melting and rain infiltrated, it gradually transformed into wet snow. There was a significant difference in the timing when the entire snowpack transformed into wet snow due to water infiltration reaching deep within the snowpack in the two winters. In 2021/22, it was mid-March, and in 2022/23, it was late January. At the time of the avalanche occurred, the entire snowpack was wet in 2021/22, and approximately 2/3 of the lower part of the snowpack was wet in 2022/23. In both years, the bottom snow layer was wet due to early-season snowmelt or rain, remaining wet throughout the winter.

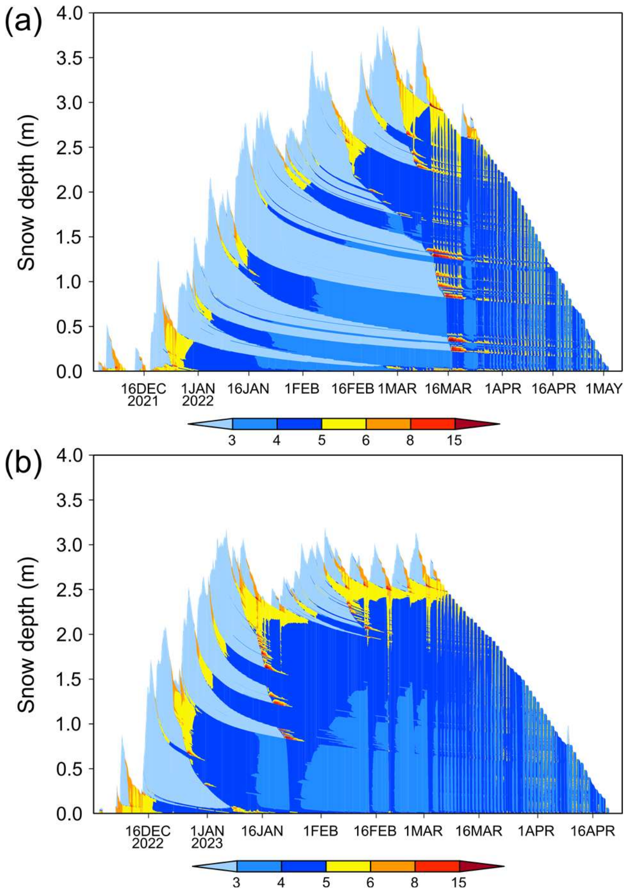

Figure 3: Temporal change of the vertical profile of volumetric water content (%) simulated by the snowpack model; (a) winter of 2021-22, (b) 2022-23.

4. DISCUSSION

Our measurements showed that a small tree with larger trunk offer larger resistive force to glide motion. It supports previous experiments where resistive force to glide was measured by connecting cut shrubs to load cells on the avalanche slope (Yamanoi, 2006). The resistive force exerted on the glide by a tree buried inside the snowpack, parallel to the slope, is due to the contact between the snow and the tree. The magnitude of the resistive force may be related to the surface area of the tree, including the canopy. The trunk diameter serves as an indicator of the tree size. Larger trunk diameters will probably lead to a larger crown, trunk length, and tree surface area. Therefore, a tree with a larger trunk diameter may provide greater resistive force to the gliding motion.

In our study, we observed a pattern where the maximum resistive force occurred earlier in the snow season, such as in December and January, followed by a decrease in resistive force. We found that the maximum resistive force came before the peak of snow depth and snow water equivalent in both winters we examined. Additionally, we noticed that resistive force decreased during periods of increased snow depth. For larger trees, we observed that the maximum resistive force appeared later than for smaller trees. Previous studies by Yamanoi (2006) and Feistl et al. (2014) suggested that increasing snow depth could lead to vegetation compaction, reducing frictional force. Our findings supported these conclusions. The trunks of measured trees were nearly parallel to the ground near their bases but gradually rose towards the tips. Snow accumulation on the tree crown and snow settlement after burial in the snowpack exert pressure on the trunk, causing the trunk to lean toward the ground. As a result, the tree's projected area relative to the direction of glide motion decreases, leading to reduced resistive force. Larger trees have more open spaces between the crown and the ground, requiring a deeper snowpack to bury the tree completely. It may explain why larger trees experienced maximum frictional force later in the season than smaller trees. Understanding the posture of tree trunks during the snow season will provide insight into trees' resistive force to gliding.

It has been noted that water at the boundary between the snowpack and the ground reduces the basal friction to gliding motion (in der Gand and Zupančič, 1965; McClund and Clarke, 1987). Then, we discuss the relationship between tree resistive force reduction and water presence on the tree-snow boundary. We assumed that the tree is buried in the snow layer formed by the snowfall when the resistive force begins to develop or immediately preceding it. The results of the snowpack simulations shown in Fig. 3 indicate that in the winter of 2021-22, snowfall occurred from 25 to 27 December and from 30 to 31 December, and in the winter of 2022-23, from 13 to 17 December and from 18 to 20 December. It is not possible to determine the exact layer of the burial. However, the tree is assumed to be buried in these snow layers. In the winter of 2021-22, no significant amounts of infiltration water occurred during January and February, and the snow layers in which the tree was buried remained dry snow. For tree B, the maximum resistive force and subsequent decrease occurred during this period. It suggests that the decrease of resistive force of tree B was caused by tree compaction due to the increased snow depth. In contrast, the resistive force of tree A continued to increase throughout this period. It appears that larger trees are less likely to develop trunk deformations that would reduce their resistance.

In winter 2021-22, water infiltration occurred frequently in March, and the entire snowpack had transformed into wet snow by mid-March. This period coincided with the period when the decrease in the resistive force of tree A started to occur. In winter 2022-23, rain-on-snow events occurred on 22 and 24 December, transforming the deeper snow layer into wet snow. After that, snowfall occurred frequently, and the snow depth increased significantly. However, the rain-on-snow event occurred again on 14 January, and most of the snow layer

transformed into wet snow. The decrease in resistive force for tree A started on the same day as the rain-on-snow event occurred, 14 January. These indicate that infiltration by rainfall and melting snow and the wet metamorphism of the snow layer, which trees bury, can trigger a decrease in tree resistive force to gliding. However, the decrease in tree resistive force due to the wetting of the snow layer is moderate rather than sudden.
An accurate understanding of the mechanism of lubrication by water at the snow-ground boundary, resulting in reduced frictional force, needs to be improved (Ancey and Bain, 2015). It has been noted that the presence of water at the snow-ground boundary causes a reduction in snow viscosity and partial separation of the snowpack from the ground, resulting in a reduction in basal friction (McClund and Clarke, 1987). Nohguchi (1989) has suggested that the reduction in the contact area between the snow and the ground due to glide progression is a factor causing a reduction in basal friction. Endo (1983) noted that gliding reduces vegetation resistive force as the vegetation gradually exits from the snowpack through the glide progression. Our measurements indicate that a state of no resistive force may occur prior to avalanche onset. In this condition, the tree and snow are not in contact with each other in a way that provides resistive force to the glide. Understanding the mechanisms by which tree resistive force is decreased might help predict the occurrence of glide avalanches on a slope on which such trees grow.

5. CONCLUSION

We measured the resistive force that small trees exerted on a snow slab just before a glide-snow avalanche. We conducted measurements on two small trees of different sizes over two snow seasons. The results showed that larger trees offer larger resistive force to glide motion. We observed a pattern where the maximum resistive force occurred earlier in the snow season, followed by a decrease in resistive force. Larger trees experienced maximum frictional force later in the season than smaller trees. The resistive force of smaller tree decreased during periods of increased snow depth. Additionally, water infiltration from rainfall and melting snow also decreased the resistive force. The maximum values for each tree remained similar in the two winter seasons. However, the timing of the appearance of these maximum values and their subsequent decrease varied for each tree and year. In years when the maximum force appeared late, the release of the glide-snow avalanche also occurred late. Deformation of the trunk due to snow loads and wet metamorphism of the snow layer where the tree is buried may decrease the resistive force of the tree. Understanding the mechanisms by which tree resistive force is decreased can help predict the occurrence of glide-snow avalanches on a slope where such trees grow.

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