Conditions under Which the Downslope Interval between Avalanche Prevention Bridges Can Be Increased and Consideration of Construction Cost Savings

H. Matsushita, M. Matsuzawa, H. Nakamura, S. Kasamura

Civil Engineering Research Institute for Cold Region (CERI), Public Works Research Institute (PWRI), Japan.   E-mail: hmatsu@ceri.go.jp

Abstract

Snow bridges are a major measure against avalanches on roads in Japan. According to the current design method, more snow bridges are required in regions where snow is not as deep, due to the shorter downslope interval between snow bridges, an interval that is proportional to the snow depth. This means that construction costs are paradoxically higher in regions with less snow. In this study, conditions under which that downslope interval can be increased were investigated through field tests and a theoretical investigation of the relationship between the increase in snow pressure and the snow compression failure condition. It was found that the downslope interval can be increased when the snow depth and slope gradient are small, for the design snow density is 350 kg m^{-3}. Trial calculations also investigated the construction cost reduction over the entire slope afforded by the decrease in the number of snow bridges resulting from the greater slope distance. In regions with relatively sparse snowfall, it will be possible to reduce the cost of constructing snow bridges by increasing the downslope interval under the conditions identified in this study.

1. INTRODUCTION

To prevent avalanches, supporting structures in avalanche start zones are designed to anchor the snow on the slope. One such structure, which has horizontal bars, is called a snow bridge. Snow that accumulates on the slope can move along the ground surface (glide) and can deform (creep) as a result of gravitational force (Figure 1). Snow bridges control the movement of snow on slopes to prevent avalanches. Such facilities are a major measure against avalanches on roads in Japan (Figure 2). For effective avalanche prevention, it is important that snow bridges be installed over the entire slope. The number of snow bridges needed for a slope depends on the downslope distance between the snow bridges (hereinafter: the downslope interval; Figure 1). However, in regions of shallower snow depth, previous reports [1] [2] have pointed out that the number of snow bridges is large and the cost is high because the downslope interval is reduced along with the depth of snow under the current design method [3] [4].

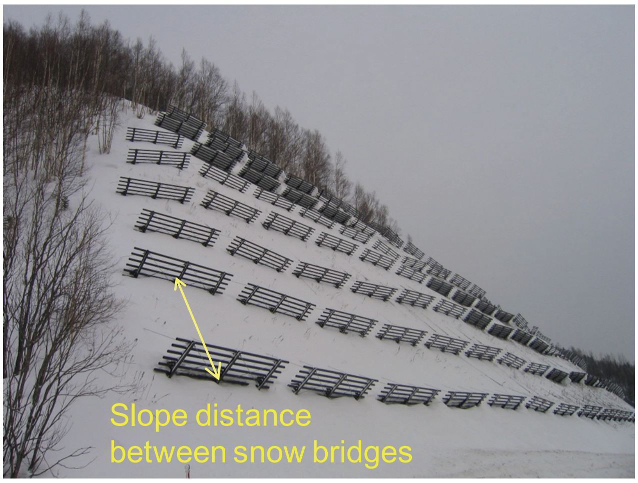


Figure 1 - An example of snow bridges installed on slope.

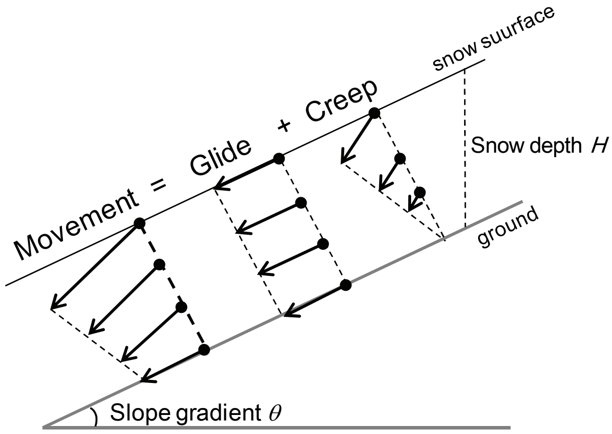


Figure 2 - Movement of snow accumulated on slope.

To address this problem, the authors have examined increasing the downslope interval between snow bridges from the current design value. This paper explains the conditions under which that interval can be increased, based on the results of field experiments [5] [6] and theoretical examinations focusing on snow cover failure [7].

2. CURRENT METHODS FOR DESIGNING SNOW BRIDGES

The snow bridges that are mainly used in Hokkaido consist of a supporting face, such as a fence, that is suspended by cables anchored upslope (Figure 3). This section explains the current method for designing the downslope interval, and issues related to that method.

2.1 Current method for designing the downslope interval

The current design method for snow bridges in Japan [4] was introduced more than 40

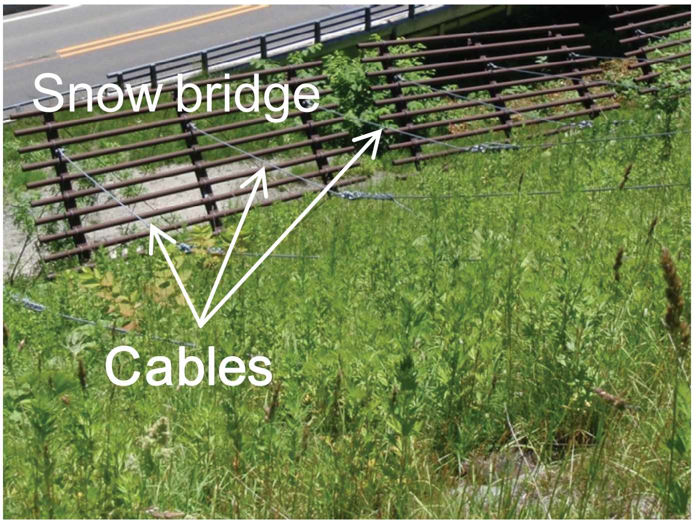


Figure 3 - Example of snow bridge used in Hokkaido.

years ago, based on Swiss guidelines [3]. In this approach, the interval between snow bridges in the downslope direction (downslope interval L) is calculated using expressions (1) and (2).

$$L = f_L \cdot H \qquad (1)$$

$$f_L = \frac{2 \cdot \tan\theta}{\tan\theta - \tan\delta} \qquad (2)$$

Here, f_L is the distance factor, H is the design snow depth (m), θ is the slope gradient (°) and δ is the angle of friction between snow and ground (°). The value of tan δ is equal to the coefficient of friction between snow and ground μ, and μ (= tan δ) = 0.5 to 0.6 is adopted [3] [4]. According to the Swiss guideline [3], on north-facing slopes and/or in Prealps regions with heavy precipitation, values lower than tan δ = 0.5 may be necessary under certain circumstances.

2.2 Deriving the expression for the downslope interval

The expression for the downslope interval is derived from two equations for the snow pressure acting on snow bridges [3] [8] [9]: the current design snow pressure for snow bridges, found using Equation (3) [4], and the theoretical snow pressure, found using Equation (4) [9].

$$S_1 = \rho g \frac{H^2}{2} KN \qquad (3)$$

$$S_2 = \rho g H \cos\theta (\sin\theta - \mu \cos\theta) L \qquad (4)$$

Table 1 - Creep factor [3]

Density of snow ρ ($kg\ m^{-3}$)	200	300	400	500	600
$K / \sin 2\theta$	0.7	0.76	0.83	0.92	1.05

Table 2 - Glide factor [3]

Classes	Ground conditions	Glide factor N	
		Slopw orientation WNW - N - ENE	Slopw orientation ENE - S - WNW
Class 1	Coarse scree ($d^* \geq 30$ cm)	1.2	1.3
	Terrain heavily populated with smaller and larger boulders		
Class 2	Areas covered with latger alder bushes or dwarf pine at least 1 m in height	1.6	1.8
	Prominent mounds covered with grass and low bushes (height of mounds over 50 cm)		
	Prominent cow trails		
	Coarse scree (d^* ca. 10 30 cm)		
Class 3	Short grass interspersed with low bushes (heather, rhododendron, biberry, alder bushes and dwarf pine below approx. 1 m in height)	2.0	2.4
	Fine scree ($d^* \leq 10$ cm) alternating with grass and low bushes		
	Smalish mounds of up to 50 cm in height covered with grass and low bushes, and also those alternating with smooth grass and low bushes		
	Grass with shallow cow trails		
Class 4	Smooth, long-bladed, compact grass cover	2.6	3.2
	Smooth outcropping rock plates with stratification planes parallel to the slope		
	Smooth scree mixed with earth		
	Swampy depressions		

d^* is the boulder diameter characteristics of the roughness of the ground surface.

Here, S_1 and S_2 are snow pressures ($N\ m^{-1}$), ρ is the snow density ($kg\ m^{-3}$), g is gravitational acceleration ($m\ s^{-2}$), H is the snow depth (m), K is the creep factor and N is the glide factor. The creep factor K depends on snow density ρ and slope gradient θ (Table 1). The glide factor N can be obtained from the ground conditions and the slope orientation as shown in Table 2. Equation (3) is derived from Haefeli's theory based on soil pressure theory and is adopted as the design snow pressure acting on snow bridges in Switzerland [3] and Japan [4] [10]. Equation (4) can be viewed as a theoretical formula for conditions where the snow movement (glide) is large and the snow on slopes is in a slippery condition [9].

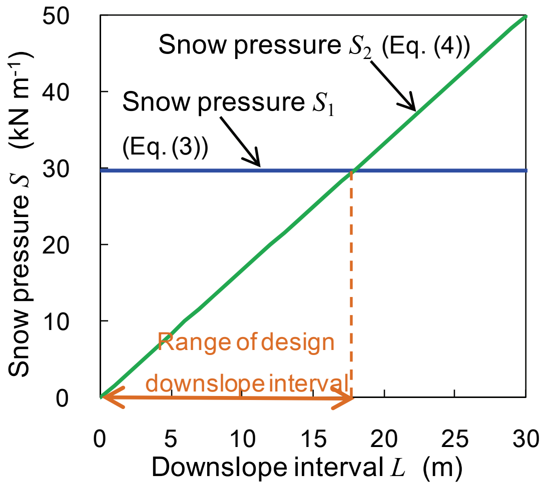


Figure 4 – Relationship between the snow pressure acting on snow bridge and the downslope interval between snow bridges.

Figure 4 compares snow pressures S_1 and S_2 given by Equations (3) and (4), relating to the downslope interval L. The snow pressure S_1 does not depend on downslope interval L. The snow pressure S_2 increases with increases in downslope interval L. The design value of downslope interval L is determined where the snow pressure S_2 in larger glide condition does not exceed the snow pressure S_1 as the static pressure. Therefore, the maximum value of downslope interval L is determined as the intersection between snow pressures S_1 and S_2. Combining Equations (3) and (4) for snow pressure as $S_1 = S_2$ obtains the downslope interval L expressed in Equation (5).

$$L = \left(\frac{K}{\sin 2\theta}\right) N \left(\frac{\tan\theta}{\tan\theta - \mu}\right) H \qquad (5)$$

The equations used to calculate the current design value of the downslope interval (i.e., Equations (1) and (2)) were obtained by inputting N = 2.7 and K/sin2θ = 0.74, the latter of which is the value found for a snow density of 270 kg m^{-3}, into Equation (5) in accordance with the Swiss guideline [8].

2.3 Problem of downslope interval under the current design method

In Equations (1) and (2), tan θ and tan δ are constants if the slope gradient and other site conditions can be considered uniform, and the downslope interval L is directly proportional to the design snow depth H. Figure 5 shows the relationship between the downslope interval L and the design snow depth H as found using Equations (1) and (2). As seen in the figure, the design downslope interval decreases with decreases in the design snow depth. This means that construction costs may be higher in areas with less snow because the downslope interval is shorter and more snow bridges need to be installed [1] [2].

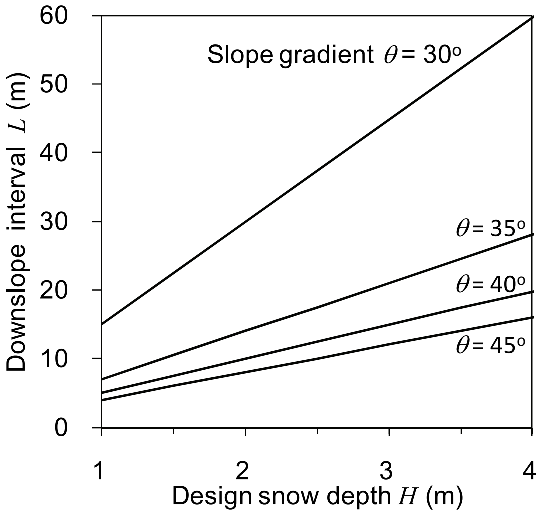


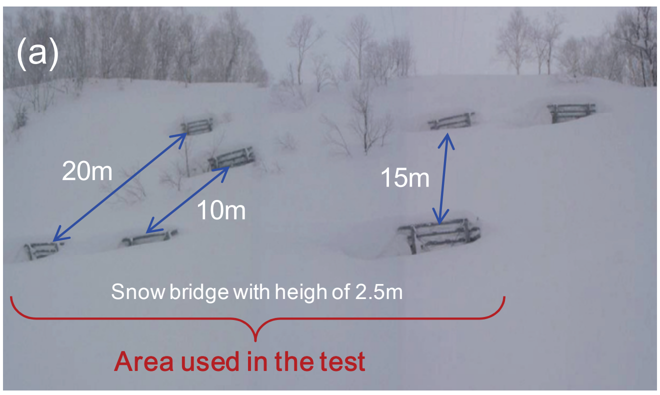
Figure 5 – Relationship between the downslope interval and the design snow depth.

3. THE CONDITIONS UNDER WHICH THE DOWNSLOPE INTERVAL CAN BE INCREASED

We will explain the conditions under which the downslope interval can be increased, based on the results of past field experiments [5] [6] and theoretical examinations focusing on snow cover failure [7].

3.1 Field tests

To support study on how the downslope interval relates to the snow pressure acting on the snow bridges, field tests were conducted on slopes at Nakayama Pass near Sapporo (mean gradient: 37°) (Figure 6) [5] and in Ashibetsu, Hokkaido (mean gradient: 29°) [6].



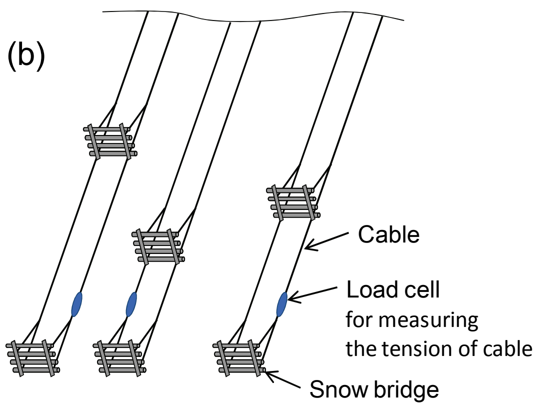


Figure 6 – (a) Condition of test site and (b) measuring the snow pressure using the load cell

The height of the snow bridges examined in the tests as found from the design snow depth was 2.5 m for the Nakayama Pass site and 1.0 m for the Ashibetsu site. The design value for the downslope interval was 15 m at both sites, and the downslope interval was varied between 10, 15 and 20 m in the tests. It was found that snow pressure did not tend to increase with increases in downslope interval at Ashibetsu, where the gradient was shallower and the snow depth was approximately 1 m [6]. However, snow pressure increased with increases in downslope interval at the Nakayama Pass site, where the gradient was steeper and the snow depth was approximately 3 m [5].

Figure 7 shows an example of the relationship between downslope interval and snow pressure at the Nakayama Pass site. However, the snow pressure data for the downslope interval of 15 m there could no longer be measured from halfway through the test. In Figure 7, the design downslope interval for the Nakayama Pass site is 15 m, which is close to the intersection between snow pressures calculated by Equations (3) and (4). When the downslope interval was 20 m (longer than the design value), the measured snow pressure was greater than the design snow pressure found using Equation (3), but was smaller than the theoretical value found using Equation (4). This suggests the feasibility of increasing the downslope interval from the current design value by taking into account the increase in snow pressure in Equation (4), even if the snow pressure acting on the snow bridges increases as a result of the greater downslope interval. However, in determining the conditions under which the downslope interval between snow bridges can be increased, it is necessary to take the increased snow pressure into account, as outlined below.

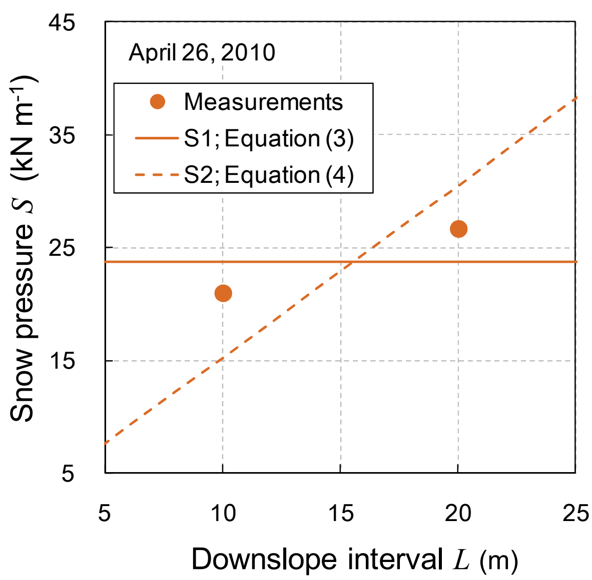


Figure 7 - Example of comparison of the measured snow pressure with the theoretical values from Eqs. (3) and (4) in the Nakayama Pass site.

3.2 Theoretical examination concerning snow failure

When the downslope interval is increased, the snow pressure is also increased, and it can be dealt with in Equation (4) by using a strong material for the snow bridges. However, there is a risk of avalanche due to failure of snow on the slope stemming from the increased snow pressure. Accordingly, the authors focused on snow cover failure conditions and compared the load applied by snow pressure and the failure strength of snow cover in order to determine the conditions under which the downslope interval between snow bridges can be increased.

On slopes with snow bridges, snow pressure is considered to be at its highest near these structures. In this study, the load due to snow pressure from snow cover was assumed to apply simply in the direction in which snow is compressed toward the bottom of the slope (Figure 8). To compare snow pressure with the failure strength of snow, it is necessary to convert the unit of snow pressure S (N m^{-1}) in Equations (3) and (4) into load per unit area P (N m^{-2}). Snow pressure per unit area P (N m^{-2}) was therefore found by dividing the snow pressure in Equations (3) and (4) (N m^{-1}) by the snow depth in the direction perpendicular to the slope Hcosθ (m) (Equations (6) and (7)).

$$P_1 = \frac{S}{H\cos\theta} = \rho g \frac{H}{2\cos\theta} KN \qquad (6)$$

$$P_2 = \frac{S}{H\cos\theta} = \rho g (\sin\theta - \mu\cos\theta) L \qquad (7)$$

The compressive strength of snow σ (N m^{-2}) was found from the relationship with snow density ρ as shown in Equation (8) for new snow and compacted snow indicated by Watanabe (1977) [11].

$$\sigma = 4.38 \times 10^{-4} \rho^{2.97} \qquad (8)$$

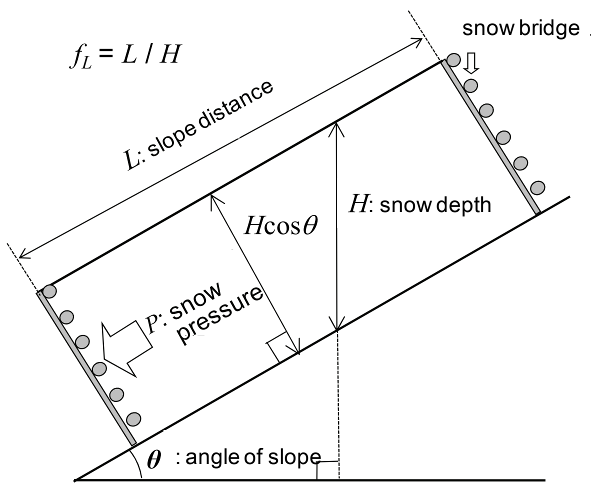


Figure 8 - Height of snow bridge and snow depth on slope.

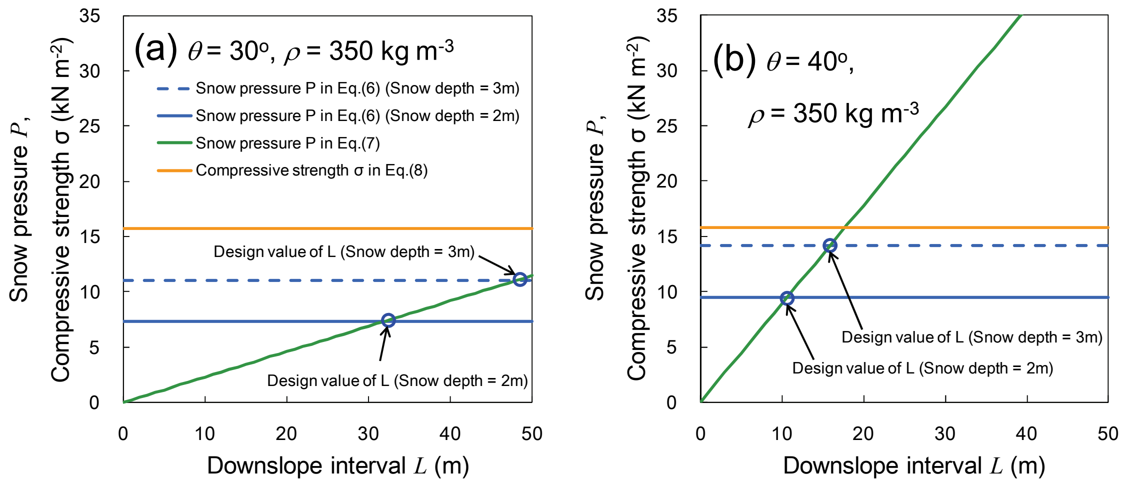


Figure 9 - Comparison between the snow pressure P and the compressive strength of snow σ for a snow density of 350 kg m^{-3} in case where the slope gradients of (a) 30 ° and (b) 40°.

Snow pressures P_1 and P_2 as found using Equations (6) and (7) were compared with the compressive strength of snow σ found using Equation (8) to determine the conditions under which the downslope interval L can be increased. Figure 9 shows snow pressures P_1 and P_2. In the calculation of snow pressure P, snow density ρ was assumed to be 350 kg m^{-3} based on the design guidelines of the Hokkaido Regional Development Bureau [10]. The coefficient of friction μ was 0.5, the creep factor K was the design value for each slope gradient θ (e.g., K = 0.69 for θ= 30°, K = 0.78 for θ= 40°), and the glide factor N was 2.7, which was used to derive the design downslope interval described in Section 2.2.

Figures 9a and 9b show the results of two cases where the slope gradient θ was 30° and 40°. The figures also show snow pressure P found using Equation (6), which is adopted for the current design, for cases with snow depth H of 2 and 3 m. In Figure 9, there are two intersections of snow pressure P found using Equations (6) and (7) for snow depth H of 2 and 3 m. These represent the downslope interval L in the current design. By shifting these intersections along the line of Equation (7), the downslope interval can be changed.

Figure 9 also shows that the compressive strength σ obtained from Equation (8) is 15.8 kN m^{-2} for snow density ρ of 350 kg m^{-3}. A comparison between snow pressure P determined using Equation (7) and compressive strength σ shows that snow pressure P increases with increases in downslope interval L and exceeds the compressive strength of snow σ when L is greater than a certain distance. If the downslope interval L is greater than the intersection between snow pressure P and compressive strength σ, then snow compression failure on the slope may occur. It is therefore necessary to satisfy the condition expressed using Equation (9) when the downslope interval L will be greater than the current design value (i.e., the intersection between Equations (6) and (7)), and this is taken as the maximum permissible value of the downslope interval L expressed in Equation (10), rewritten from

Equation (9).

$$\sigma > P_2 = \rho g(\sin\theta - \mu\cos\theta)L \qquad (9)$$

$$L < \frac{\sigma}{\rho g(\sin\theta - \mu\cos\theta)} \qquad (10)$$

3.3 Feasibility of increasing the downslope interval from the current design

The field test and the theoretical examination indicated that the downslope interval can be increased from the current design value when the snow compressive strength exceeds the snow pressure. In the Swiss guideline [3], however, the maximum distance factor f_L is determined as 13 for the maximum permissible value of downslope interval. In this study, we use f_L = 13 in accordance with the Swiss guideline [3]. Therefore, it will be possible to increase the downslope interval when two conditions are satisfied:

(I) the snow pressure does not exceed the compressive strength (Eq. (10)), and

(II) the distance factor f_L (L / H) is less than 13.

Figure 10 summarizes the conditions under which the downslope interval can be increased from the current design. The figure shows the results of cases in which the snow density was assumed to be 350 kg m^{-3} in accordance with the design guidelines of the Hokkaido Regional Development Bureau [10]. It shows the design values of the downslope interval for snow depths of 2 and 3 m. It also shows the relationship between slope gradient θ and the downslope interval L (the intersection between snow pressure P_2 and compressive strength of snow σ shown in Figure 9) at which the snow pressure P_2 in Equation (7) becomes the same as the compressive strength σ.

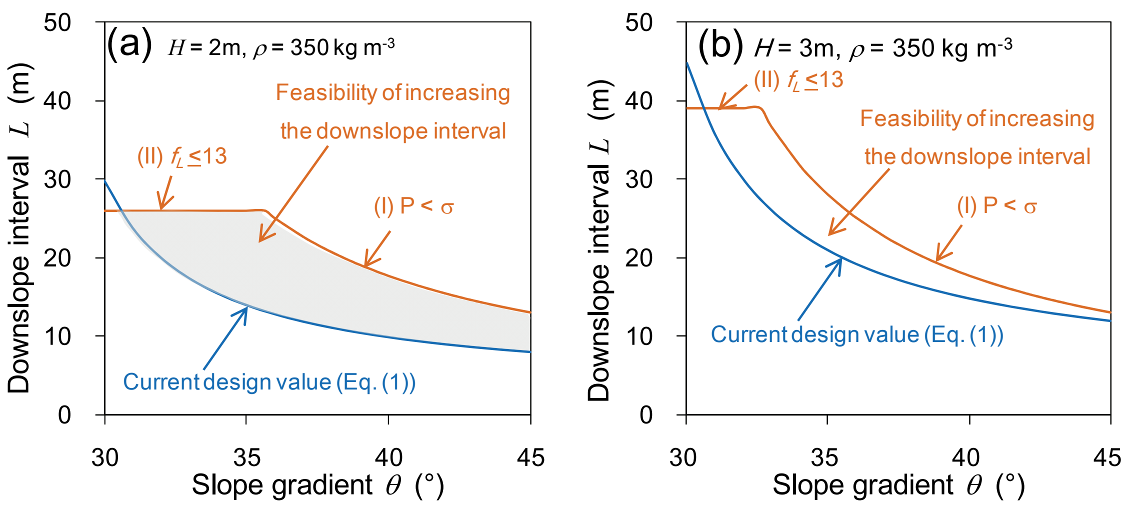


Figure 10 - Conditions under which the downslope interval can be increased from the current design for snow depth of (a) 2 m and (b) 3 m.

It can be seen from Figure 9 that the design downslope interval is shorter than that found from the compressive strength of snow with the snow depth of 2 m, and that the design condition is on the safe side. In other words, there is leeway to increase the downslope interval found in the current design. However, for the snow depth of 3 m, the design value was closer to that found from the compressive strength. Accordingly, it is presumed that the downslope interval can be increased mainly in cases where snow depth and slope gradient values are small.

4. THE CONTSRUCTION COST OF SNOW BRIDGES

We also attempted to calculate the cost of constructing snow bridges for a case in which the downslope interval is increased, under conditions (I) and (II), from the current design value. The trial calculations were conducted for slope with gradient of 35°, 40° and 45° and with a length of 100 m. Snow bridges with a width of 5.5 m were used in this calculation. In the calculation, snow depths were 2 m and 3 m, snow density was 350 kg m^{-3} and glide factor N was 2.6. Other conditions, such as materials used, were based on the design guidelines of the Hokkaido Regional Development Bureau [10] and the specifications for highway bridges [12].

Figure 11 shows the ratio of the construction cost for snow bridges installed with the increased downslope interval to the construction cost for snow bridges installed based on the current design method. Figure 11 also shows a comparison between the material costs for the snow bridges in each method. The trial calculations suggest a cost reduction for snow bridges over the entire slope, although the material cost per snow bridge may be higher due to increased snow pressure. The installation cost reduction in the case of the snow depth of 2 m is much greater than that in the case of the snow depth of 3 m.

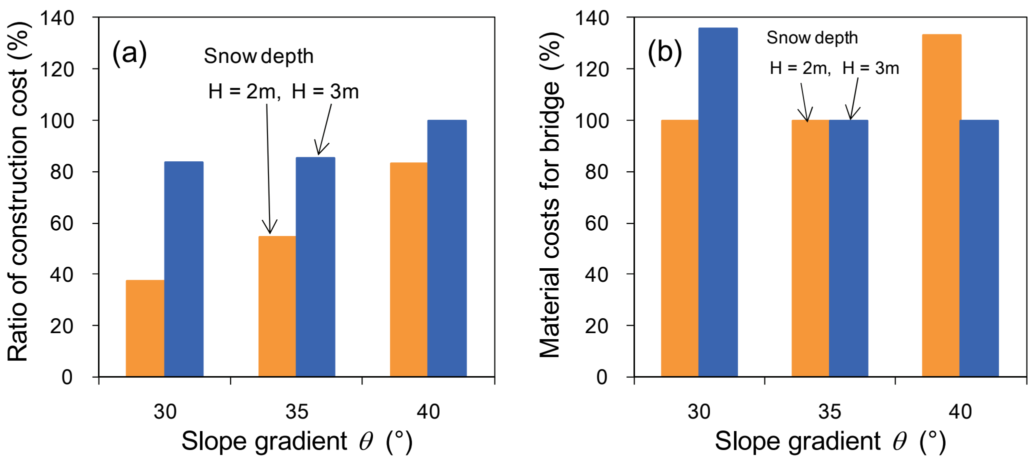


Figure 11 - (a) The ratio of the construction cost for snow bridges installed with the increased downslope interval to the construction cost for snow bridges installed based on the current design method, and (b) comparison between the material costs for the snow bridges in each method.

Therefore, using the conditions proposed in this study will make possible to reduce the cost of constructing snow bridges in regions with relatively scant snow by increasing the downslope interval.

5. CONCLUSION

This study investigated the conditions under which the downslope interval between snow bridges can be increased, based on field tests and a theoretical comparison between the increase in snow pressure and the conditions under which snow compression failure occurs. It was found that the downslope interval can be increased when the design snow density is 350 kg m^{-3} in cases where the snow depth and slope gradient are small. The trial calculations also suggest that the greater downslope interval affords cost reductions over the entire slope, due to the decreased number of bridges necessary. Therefore, using the conditions proposed in this study will make it possible to increase the downslope interval and, thus, to reduce the cost of constructing snow bridges in regions with relatively scant snow.

It should be noted that the study was conducted for compacted snow with a density of 350 kg m^{-3}, and separate investigation should be performed for areas characterized by low-density snow [7] and granular snow with lower compressive strength [11].

References

1. Matsuzawa, M., 2008. Why does the number of avalanche bridges increase when the design snow depth becomes small?. Consultants Hokkaido, 115, 45-47. [In Japanese]
2. Otsuki, M., 2009. Problems of design method for avalanche prevention facilities -About slope distance between two rows of snow fences-. Journal of Snow Engineering of Japan, 25(4), 270-275. [In Japanese]
3. Margreth, S., 2007. Defense structures in avalanche starting zones. Technical guideline as an aid to enforcement. Environment in Practice no. 0704. Federal Office for the Environment, Bern; WSL Swiss Federal Institute for Snow and Avalanche Research SLF, Davos, Switzerland, pp134.
4. Japan Construction Mechanization Association (JCMA) and Snow Research Center (SRC), 2005. Avalanche protection. 2005 Handbook for Snow Removal and Snow Hazard Control, 143-246. [In Japanese]
5. Matsushita, H., M. Matsuzawa, H. Nakamura, and O. Sakase, 2012a. An examination for determining the slope distance between avalanche prevention bridges. Proceedings of the 7th International Conference on Snow Engineering, 69-79, Fukui, Japan, June 2012.
6. Matsushita, H., M. Matsuzawa, H. Nakamura and S. Kasamura, 2012b. Snow pressure acting on snow bridges for avalanche prevention regarding slope distance between bridges in slope of low gradient. Hokkaido no Seppyo, 31, 163-166. [In Japanese]
7. Matsushita, H., M. Matsuzawa and H. Nakamura, 2012c. Possibility of increasing the slope distance between avalanche prevention bridges. Proc. International Snow Science Workshop (ISSW), 696-702,

Anchorage, USA, September 2012.
8. Shoda, M., et al., 1966. Design manual of avalanche defense structures. Douro, 63-73. [In Japanese]
9. Endo, Y., 2000. snow movement and stress distribution on slope. Avalanche and blowing snow (N. Maeno and M. Fukuda (Ed.)), Kokon-shoin, Tokyo, Japan, 24-42. [In Japanese]
10. Hokkaido Regional Development Bureau (HRDB), 2010. Guideline for road design. The second collection, road facilities. [In Japanese]
11. Watanabe, Z., 1977. The influence of snow quality on the breaking strength. Sci. Rep. Fukushima Univ., 27, 27-35.
12. Japan Road Association (JARA), 2008. The specifications for highway bridges (JARA, 2012), Part II Steel bridges, pp439.