# Thermal, hydraulic and mechanical stabilities of slopes covered with *Sasa nipponica*

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ABSTRACT: Following a comprehensive field study evaluating thermal, hydraulic, and mechanical stabilities of a slope covered with *Sasa nipponica,* a type of dwarf bamboo (known as *Sasa*), against slope failure in a cold region (eastern Hokkaido in Japan), it was found that thermal stability increases due to a decrease in freezing and frost heaving of the surface layer caused by the adiabatic effects of *Sasa* litter and the snow it retained. Further, *Sasa* plays a role in reducing the effect of rainfall due to the water retention by the *Sasa* rhizome layer in the surface soil, thereby increasing hydraulic stability. Through surveys of surface failures caused by an earthquake in places on wild slopes covered with *Sasa*, the mechanical stability was evaluated using the safety factor in a static condition expressed as a function of the leaf area index (LAI), which exceeds 1.37, owing to the reinforcing effect of the rhizomes.

## 1 INTRODUCTION

On the artificial slopes along roads in cold regions, slope surface failure and erosion occur occasionally owing to frost heave damage to protective grids, which usually cease to function because they protrude from the ground surface due to repeated freeze–thaw cycles, as shown in Figure 1. In Japan, these grids are generally used to keep the planting ground on steep slopes stable, but the damage is mainly concentrated in eastern Hokkaido, as shown in Figure 2 (Takeda et al. 2000). On the other hand, hardly any damage occurs on native slopes covered with *Sasa nipponica* Makino et Shibata (called *Sasa*), a type of dwarf bamboo, especially to grow in such the cold region, which has less snow, illustrated in Figures 2 (Hokkaido 1983) and 3.

Figure 1. Surface failure on the artificial slope and frost heave damage to protective grids, marked with a circle (left).

In general, rhizomes of *Sasa* species characteristically have strong tensile strength (Takeda et al 2001), the same as that of a tree (O'Louglin et al. 1982), allowing it to uniformly cover the ground and form a surface layer (Karisumi 1969) like a mattress on slopes (called a *Sasa* mat). Comparing native and artificial slopes, it is expected that *Sasa* lessens the effects of frost such as frost depth and the amount of frost heave in the surface layer of the slope (Takeda et al. 1999). During rainfall, the above-ground part seems to mitigate the impact of raindrops, and the underground parts temporarily retain water and to drain it for a long time like a surface soil of forest (Ohta 1990). Further, it is anticipated that the rhizomes growing in the surface layer consolidate the soil to prevent sliding and slope failure (Karisumi 1987). Although the slope stability caused by effects of tree roots has been studied such as Wu et al. (1979) and Tsukamoto (1987), any stability by that of the rhizomes hardly has been done. They cannot be applied adequately to the design and construction of slopes to prevent disasters, because these functions of *Sasa* are not well understood quantitatively for the slope stability.

In this study, for clarifying quantitatively the functions of *Sasa* for thermal, hydraulic, and mechanical stability of slopes to prevent slope failure, a comprehensive field study and a laboratory test were conducted on flat ground and slopes covered with *Sasa*.

## 2 STUDY METHODS

The studies consist of a field observation, a field survey, and a laboratory test.

### 2.1 *Observation of the thermal effects of Sasa*

To estimate the thermal environment formed by *Sasa*, the seasonal maximum values of frost depth and heave amount were observed in November 1994–April 1995 at 10 spots on the ground where *Sasa* grows densely or sparsely, located on a hill along the coast in Urahoro in Hokkaido, marked with ① in Figure 2. These spots, including bare ground, are established on frost-susceptible soil, and are almost flat to eliminate the influence of the slope's direction. The difference in the growth density was expressed as the culm density of *Sasa*, given by the number of culms in 1 $m^2$. In this observation, the frost depth and heave amount were measured using a frost tube that detected the depth from the disturbed traces of blue-colored jelly by methylene blue in the tube due to freezing and a newly devised displacement gauge having a screw-type anchor that is screwed deeper than the maximum frost depth, respectively. Further, the air and ground temperatures were measured.

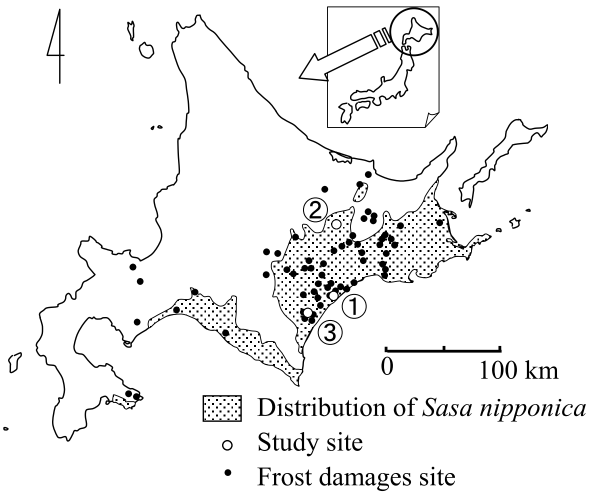

Figure 2. Study sites and distributions of frost heave damage and *Sasa nipponica* in Hokkaido, Japan.

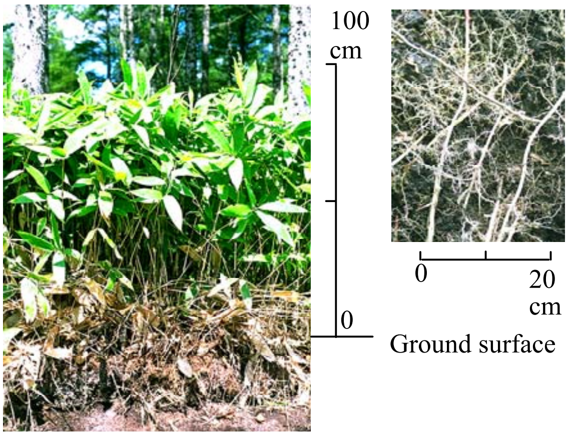

Figure 3. Cross section of the ground covered with *Sasa nipponica* (left) and its rhizomes (right).

### 2.2 *Observation of the hydraulic functions of Sasa*

To evaluate the hydraulic functions of *Sasa*, the water balance was compared on slopes covered with and without *Sasa*. On a slope near Rikubetsu (marked ② in Fig. 2), which has a gradient of 20° and faces southwest, we partly stripped away the *Sasa*, including the rhizomes. Then, the sites covered with and without *Sasa*, called the *Sasa* site and the bare site, 5 m in width × 5 m in slope length, and 1 m × 5 m, respectively, were prepared for observation by enclosing their upper ends and sides with zinc to a depth of 60 cm to avoid inflow of water.

Because the surface of the *Sasa* site, consisting of the organic soil layer including a *Sasa* mat 25 cm thick and volcanic sand layers 1 and 2, is established as the surface level, the surface of the bare site, consisting of only the latter two, is 25 cm below the surface, as shown in Figure 4. To calculate the water balance, suction was automatically measured using a tensiometer (indicated as a circle in Fig. 4) at 10 cm, 35 cm, and 50 cm depth (D10, D35, and D50) in the *Sasa* site, and at 35 cm and 50 cm (D35 and D50) in the bare site, from July through September 2000. In addition, the outflow rate was measured at 25 cm and 55 cm depths at the lower end of both sites using a run 1m wide and a rain gauge. The precipitation, air temperature, and surface temperature were also measured. Using the soil moisture characteristic curve obtained in the laboratory tests, suction during

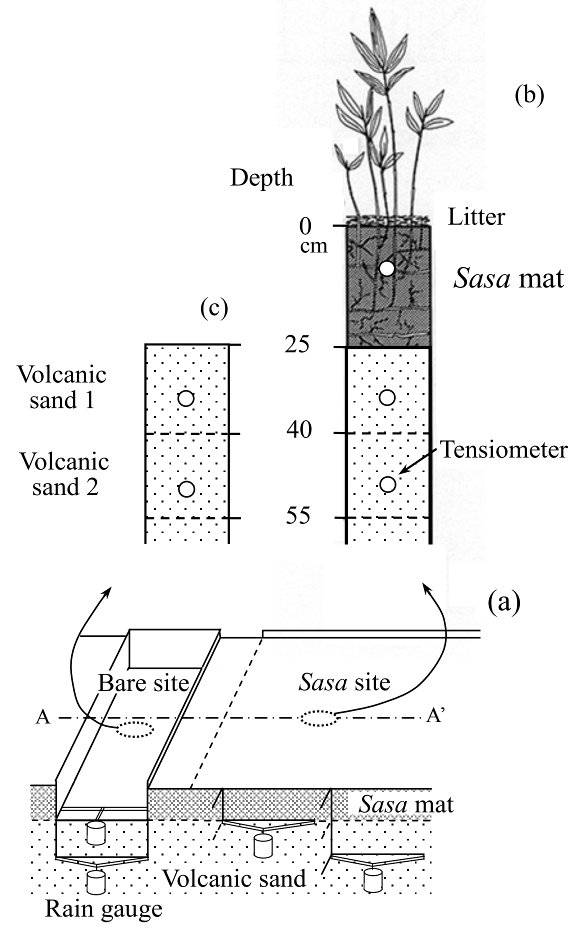

Figure 4. Outline of study sites (a), and cross sections of *Sasa* (b) and bare sites (c).

heavy rains was converted into volumetric water content, which was then used for calculating the water balance.

### 2.3 *Survey of the mechanical functions of Sasa*

To evaluate the stability of the surface layer on slopes reinforced by *Sasa*, field surveys and laboratory tests were conducted on the native slope covered with *Sasa* on which partial sliding surface failures occurred due to the earthquake (January 1993, M7.8) at Taiki, as indicated by ③ in Figures 2 and 5. The following procedures were carried out: (1) field survey of surface sliding on the slope; (2) vegetative investigation for *Sasa* on the slope; (3) laboratory tension test for the rhizomes; and (4) laboratory direct shear test for soil sampled at the sliding surface on the slope. In addition, by the vegetative investigation, the relationship between the above- and below-ground parts of *Sasa* on the slope was investigated in eastern Hokkaido (Takeda et al. 2003).

Figure 5. Surface failure on the wild slope covered with *Sasa nipponica* induced by the earthquake.

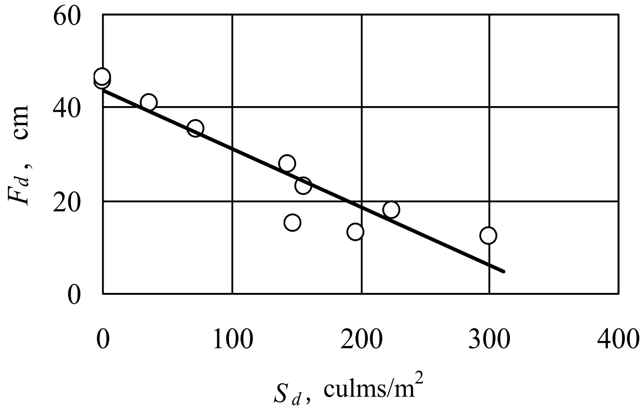

Figure 6. Relationship between the seasonally maximum frost depth $F_d$ and the culm density of *Sasa nipponica* $S_d$.

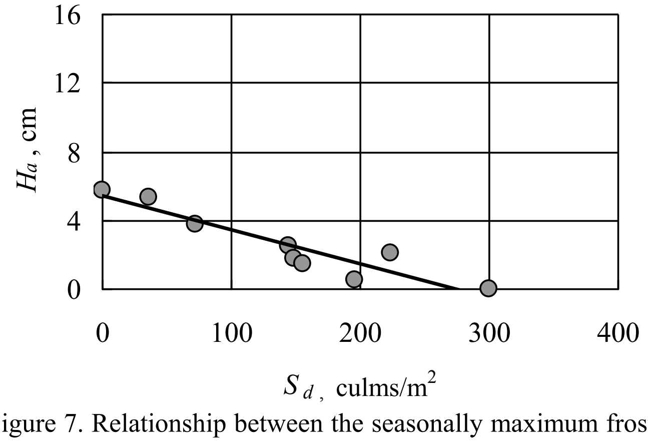

Figure 7. Relationship between the seasonally maximum frost heave amount $H_a$ and the culm density of *Sasa nipponica* $S_d$.

## 3 RESULTS

Based on the studies, the estimation of the thermal, hydraulic, and mechanical effects of *Sasa* are presented as follows.

### 3.1 *Thermal effects of Sasa*

As shown in Figures 6 and 7, both the seasonally maximum values of frost depth $F_d$ (cm) and heave amount $H_a$ (cm) decrease with increasing of culm density $S_d$ (culms/m$^2$), given by the following equations:

$$F_d = -0.126\,S_d + 43.8 \tag{1}$$

$$H_a = -0.0198\,S_d + 5.40 \tag{2}$$

Further, using the daily temperature changes at 5 cm and 0 cm above the surface, the thermal conductivity of the litter layer and the snow cover retained by *Sasa* was calculated, based on the difference in oscillations observed when the change is regarded as a sine curve (Com. Meth. Phys. Prop. Soil 1978, Takeda et al. 1999). It was estimated to be 0.035 W/mK, indicating that *Sasa* works like a thermal insulating material available in the market in extruded polystyrene forms (Jpn. Soc. Thermophysical Prop. 1990).

When frozen soil thaws, slope failure often occurs at the boundary of thawing and frozen layers. Therefore, since the frost action occurs in the *Sasa* mat on the *Sasa* slope owing to the decrease in the frost depth and heave amount, the thermal stability of the slope increases.

### 3.2 *Observation of suction in surface layers during rainfall*

During the observation, two rainfalls offered suitable opportunities to observe large changes in the suction (July 15–18 and September 24–25). Observation results for the former event are shown in Figure 8, which shows changes in precipitation, suction, and outflow. The suction responds sensitively to the two peaks of precipitation, 8.5 and 15.2 mm/h. Also, the outflow changes considerably on the surface of the bare site (25 cm in depth), while there is hardly any change at 25 cm below the *Sasa* mat. Using the soil moisture characteristic curve obtained in laboratory tests, the suction is converted into the volumetric water content, as presented in Figure 8 (g). During this observation, the total precipitation was 33.2 mm. On September 24–25, similar results were obtained when the total precipitation was 32.2 mm. Further, the amount of evaporation was calculated by the bulk method using the surface temperature of both sites and the air temperature, and confirmed to be negligible small (Kondo, 1999). Also, to estimate the capacity of rainfall intercepted by the aboveground part of *Sasa* and its litter, the water retained in a unit area 1 m$^2$ was 842 cm$^3$ from the laboratory test. Through the calculation of water balance using the results, it was found that the average percentage of precipitation retained in the *Sasa* mat was 77%, from 79.8% and 73.8% shown in Table 1, while the infiltration at the bare site averages 71%.

Since a comparison showed that the downward force of the Sasa mat that retains rainwater is less than 10% that of the resistance to sliding, such as the tensile force of the rhizomes and the soil strength, it was verified that the hydraulic stability increases by *Sasa* coverage (Takeda et al. 2008).

### 3.3 *Mechanical stability of the slope*

To estimate the mechanical stability of the slope covered with *Sasa*, we used the survey results of the sliding surface and found that the slope length is 33 m, the width 45 m, the average gradient $\alpha$ 40°, the average thickness $H$ 0.6 m, the direction 135° clockwise from the north, and the area $S$ 1,041 m$^2$. Based on the results, a model for analysis was established, as presented in Figure 9. In this model, the safety factor is expressed as a function of the tensile force of rhizomes per unit slope length, considering the seismic acceleration $K_h$, as follows: where the symbols

$$F_s' = \frac{L}{S H \gamma_t (\sin\alpha + K_h \cos\alpha)} t + \frac{c + H\gamma_t(\cos\alpha - K_h \sin\alpha) \tan\phi}{H\gamma_t(\sin\alpha + K_h\cos\alpha)} \qquad (3)$$

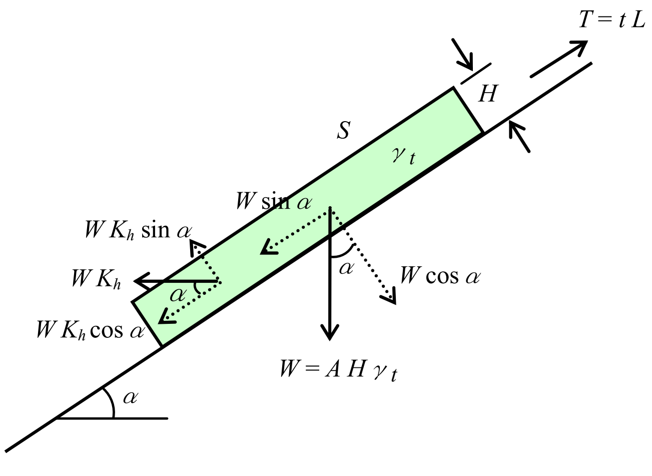

Figure 9. Analysis model for the mechanical stability of wild slope covered with *Sasa nipponica*.

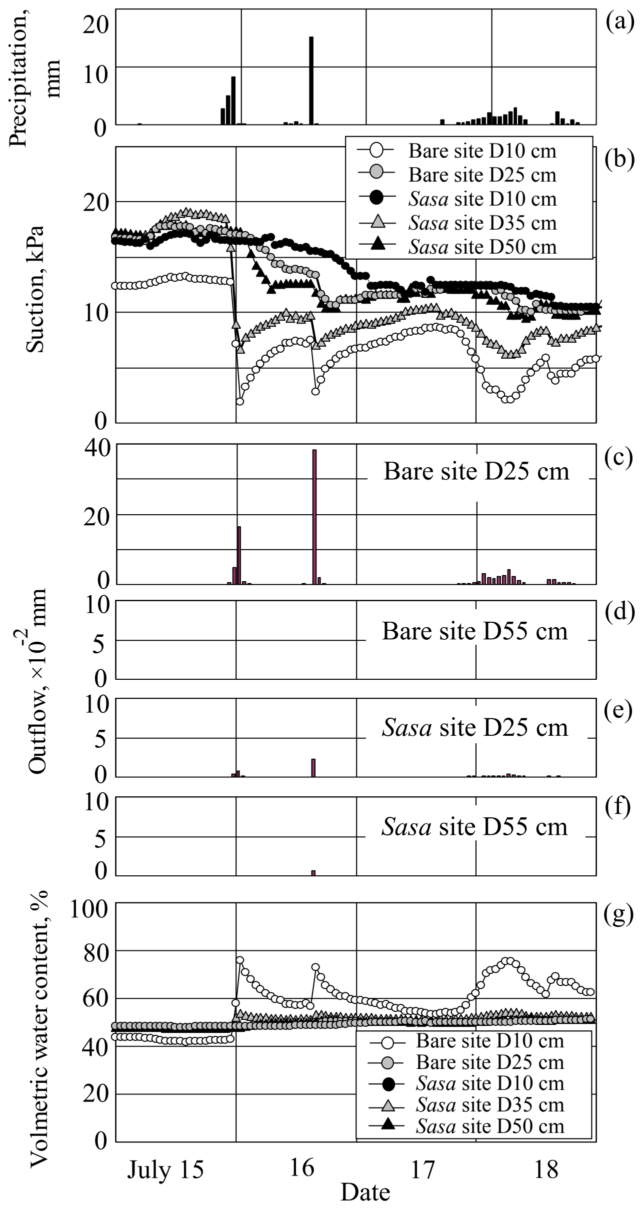

Figure 8. Changes of precipitation (a), suction (b), outflow (c) – (f), and volumetric water content (g) at the *Sasa* and bare sites on the slope.

Table 1. Water balance at the *Sasa* and bare sites.

| Duration of rainfall | July 15 22:00–16 17:00 | | September 24 15:00–25 22:00 | |
|---|---|---|---|---|
| (a) Water balance at the *Sasa* site | | | | |
| Amount & Percentage | l* | % | l* | % |
| Precipitation | 166.0 | 100.0 | 161.0 | 100.0 |
| Interception of *Sasa* Surface (D0cm) | 4.2 | 2.5 | 4.2 | 2.6 |
| *Sasa* mat | 132.5 | 79.8 | 118.8 | 73.8 |
| Outflow D25cm | 0.2 | 0.2 | 0.1 | 0.1 |
| Volcanic sand 1 | 16.5 | 9.9 | 24.8 | 15.4 |
| Volcanic sand 2 | 11.3 | 6.8 | 12.8 | 7.9 |
| Outflow D55cm | 0.0 | 0.0 | 0.1 | 0.1 |
| Infiltration | 1.3 | 0.8 | 0.2 | 0.1 |
| (b) Water balance at the bare site | | | | |
| Precipitation | 166.0 | 100.0 | 161.0 | 100.0 |
| Outflow D25cm | 3.2 | 1.9 | 6.8 | 4.2 |
| Volcanic sand 1 | 25.5 | 15.4 | 25.5 | 15.8 |
| Volcanic sand 2 | 17.3 | 10.4 | 18.0 | 11.2 |
| Outflow D55cm | 0.0 | 0.0 | 0.1 | 0.0 |
| Infiltration | 120.0 | 72.3 | 110.6 | 68.7 |

* Total amount (l) in the range of 1 m (W)×5 m (L)

and values obtained from the field investigation and the laboratory tests, are summarized in Table 2, $W$ ($= S\,H\,\gamma_t$) is the weight of the sliding layer, and $T$ ($= t\,L$) is the tensile force of rhizomes around the sliding layer.

As shown in Figure 10, the safety factor during the earthquake is determined to be about 1.0; thus, the result can be considered relevant, because five surface failures were found distributed on slopes in the range of 1 km. For the other two failures of them analyzed in the same manner (Takeda et. al., 2001), the factors were about 1.0. Next, assuming that we can apply these values to the estimation of the safety factor in the static condition, it was determined to be 1.26 on the slope without *Sasa*, and more than 1.37–1.65 using $t$ values of 5.8–20.3 kN/m. Therefore, it was found that the increases in the factor with the tensile force indicate the reinforcing effect of rhizomes on the surface layer of the slope, while the factor for the slope without *Sasa* is dependent on the strength parameters of soils at the sliding surface.

## 4 DISCUSSION

The results of the study indicate that the thermal, hydraulic, and mechanical stabilities of the slope increase due to the *Sasa* cover. The functions for evaluating each type of stability are different, but it is necessary to establish a common function when the stability is synthetically discussed. Moreover, it is more important for the function to sample easily. Thus, as the function, we used the leaf area index (LAI, $m^2/m^2$), which is the total leaf area in a unit area 1 $m^2$ to represent the activity of the above-ground part of *Sasa*.

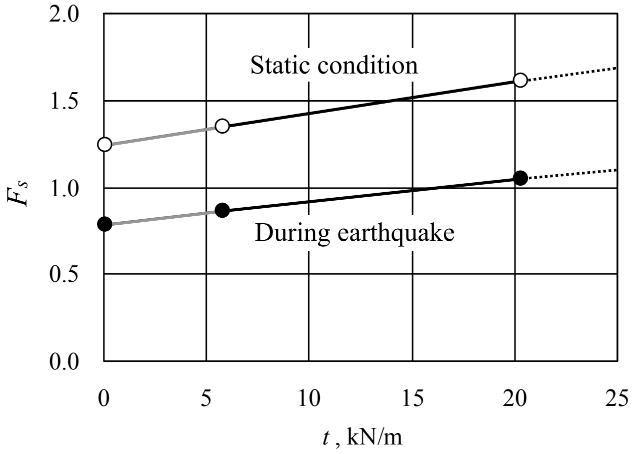

Figure 10. Relationship between safety factor $F_s$ and tensile force of *Sasa* rhizomes per unit slope length $t$.

Table 2. Values used in the analysis for slope stability.

| Items for analysis | Values |
|---|---|
| Unit weight of failed slope $\gamma_t$, kN/m$^3$ | 9.5 |
| Tensile force of rhizomes per unit sectional length of slope surface layer $t$, kN/m | 0.0,<br>5.8–20.3 |
| Length of broken part around the failed slope $L$, m | 73.1 |
| Cohesion at the sliding surface $c$, kPa | 2.35 |
| Internal friction angle at the sliding surface $\phi$ ° | 27.5 |
| Ratio of horizontal seismic acceleration to gravity, $K_h$* | 0.335 |

* National Res. 1993

For evaluating thermal stability, the culm density is converted into LAI by the dry weight and the dry density of leaves. From the results of 12 other investigation sites in the field and flat ground in eastern Hokkaido (Takeda et al. 2003), the mean value of LAI, 0.60 $m^2/m^2$, is modified to a September value of 0.69 $m^2/m^2$ by seasonal correction, and that of culm density is obtained as 99.9 culms/$m^2$ (Agata et al. 1979). From these values, the maximum frost depth and heave amount in Equations (1) and (2) are given as a function of LAI, as follows:

$$F_d = -18.3\,\mathrm{LAI} + 43.8 \tag{4}$$

$$H_a = -2.88\,\mathrm{LAI} + 5.40 \tag{5}$$

When the hydraulic stability is discussed, the percentage of the water remaining in each layer after precipitation, the water retention rate $w_r$ (%), is defined. The mean $w_r$ of the values from both rainfall events, 79.8% and 73.8%, is 76.8% on the *Sasa* slope, while the mean for the bare slope is 15.6%. Further, the LAI on the *Sasa* and bare slopes were 4.35 and 0 $m^2/m^2$, respectively. For about 30 mm of precipitation during a few days, when it is assumed that $w_r$ linearly increases with LAI, the relationship is presented as the following equation:

$$w_r = 14.1\,\mathrm{LAI} + 15.6 \tag{6}$$

Since $w_r$ is generally considered to increase with the dry weight of the underground part and LAI increases with the weight (Takeda et al. 2003), the above equation is regarded as relevant.

To evaluate the mechanical stability of the slope covered with *Sasa*, the safety factor is presented as a function of the tensile force of rhizomes per unit sectional length of the slope surface layer. Through the field survey and the laboratory test, the force is given by the product of the sectional area of rhizomes and their tensile strength $p$ (MPa). Since the relationship between LAI and the accumulated sectional area of rhizomes per unit sectional length of slope surface layer $S_r$ is also obtained by the other surveys at 17 sites of the slopes covered with *Sasa*, given in rhizomes per unit sectional length of slope surface (see Eq. (7) and Fig. 11), the tensile force $t$ is presented by LAI and $p$ as Equation (8),

$$S_r = 1.26\,\mathrm{LAI} + 1.03 \tag{7}$$

$$t = (1.26\,\mathrm{LAI} + 1.03) \times p \tag{8}$$

where $p$ is in the range 8.4–33.8 MPa. Moreover, as $F_s$' in Equation (3) was found to be a linear relationship as a function of $t$, the factor $F_s$ is generalized by use of Equation (8) as a function of LAI as follows.

$$F_s = \frac{L\,p\,(1.26\,\mathrm{LAI} + 1.03)}{S\,H\,\gamma_t\,(\sin\alpha + K_h\cos\alpha)} + \frac{c + H\gamma_t\,(\cos\alpha - K_h\sin\alpha)\,\tan\phi}{\mathrm{H}\,\gamma_t\,(\sin\alpha + K_h\cos\alpha)} \qquad (9)$$

As these equations indicate, the stability is evaluated as a function of LAI representing the aboveground part of *Sasa*, without surveying the underground part.

## 5 CONCLUSION

The results of a field survey and laboratory test were analyzed and discussed. The following conclusions could be made:

1 *Thermal stability*: The annual maximum values of frost depth and frost heave amount of the surface layers on the slope are significantly suppressed by the *Sasa* cover, so that the thermal stability of slope increases.

2 *Hydraulic stability*: Once a *Sasa* mat has formed on the surface layer of the slope, the water retention increases remarkably, as does the hydraulic stability.

3 *Mechanical stability*: Using the surface failure on the *Sasa*-covered slope caused by the earthquake, the mechanical stability is evaluated by the safety factor in the static condition expressed as a function of leaf area index (LAI), which exceeds 1.37 owing to the reinforcing effect of rhizomes.

As *Sasa nipponica* grows not only in eastern Hokkaido, but also in the area along the Pacific Ocean from Honshu to the Kyushu Islands in Japan (Suzuki 1978), this evaluation can be applied to slope protection techniques in warmer areas, which has less snow.

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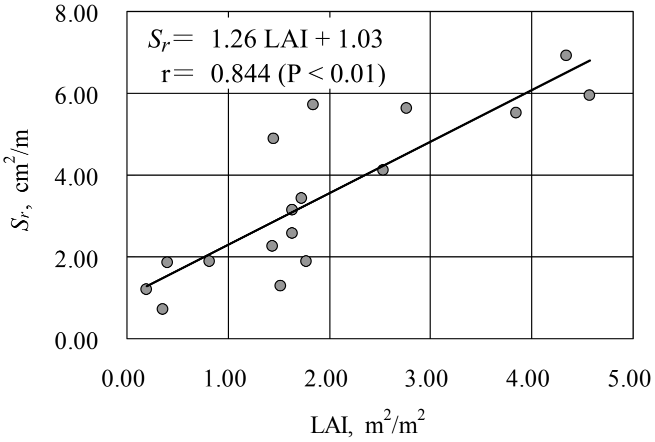

Figure 11. Relationship between the leaf area index (LAI) and the accumulated cross sectional area of rhizomes per unit sectional length of slope surface layer $S_r$.

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