SHEAR STRENGTH OF NATURAL AND ARTIFICIAL DEPTH HOAR LAYERS

Osamu ABE*, Junrong XU**, Jian LIU***, Hiroyuki HIRASHIMA*, Shigeto MOCHIZUKI*,
Satoru YAMAGUCHI*, Takeshi SATO* and Atsushi SATO*
* National Research Institute for Earth Science and Disaster Prevention, Japan
** Xinjiang Institute of Ecology and Geography, Urumqi, China
*** Xinjiang Institute of Communications, Urumqi, China

ABSTRACT: Many data on shear strength and density of natural depth hoar layers were collected from Japan, west China and Alaska. Snow metamorphism experiments under temperature gradient conditions were conducted in a large cold room using two types of artificial snow that consist of dendrite or ice sphere particles, and shear strength and density for each layer were measured at the different stages. Eighty-three data on shear strength of natural and artificial snow layers were combined with two groups according to the grain shape, and were correlated with density by two types of equations for faceted and cup-shaped crystals. Based on the equations, the presented shear strength of cup-shaped crystals was smaller than that measured in North America with the same density, but the shear strength of faceted crystals increased quickly for snow density > 300 kg m^{-3}.

KEYWORDS: shear strength, depth hoar, avalanche occurrence

1. INTRODUCTION

Snow avalanches with failure layers of depth hoar are sometimes observed in high mountainous areas of Japan (Akitaya et al., 1990; Hirashima et al., 2005). Many data on shear strength of depth hoar layers measured in Europe and North America were reported (Fohn et al., 1998; Jamieson and Johnston, 2001), but there are a few data in Asia (Hu and Jiang, 1989; Akitaya et al., 1990; Kaihara, 1998; Qiu, 2004). Shear strength of depth hoar is usually expressed as a function of its density. However, depth hoar layer may have a wide variation, depending on its developing stage. We have collected data on shear strength with density of depth hoar layers in fields and in a cold room. The shear strength was measured using a shear frame with an area of 0.025 m^2. For the field observation, several high elevation and/or cold areas were selected in Japan, west China, and Alaska. Furthermore to prepare an artificial depth hoar layers, several experiments on snow metamorphism were conducted in a large cold room with two kinds of artificial snowfall machines. In these experiments new snow or compacted snow were prepared, and were exposed to negative temperature gradients.

2. MEASUREMENTS OF SHEAR STRENGTH

The shear strength of depth hoar layers was measured using a shear frame with an area

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* Corresponding address: Osamu ABE, Shinjo Branch, Snow and Ice Research Center, NIED, 1400 Tokamachi, Shinjo 996-0091 Japan
email: oabe@bosai.go.jp

of 0.025 m^2, as recommended by Sommerfeld (1984) (Fig. 1). In accordance with the shear frame - test procedure described by Jamieson and Johnston (2001), the shear frame was inserted onto the weakest layer and pulled smoothly and quickly (in < 1 s). The attached force gauges had full load capacity of 100 N. The shear strength without an overburden load was determined by dividing the maximum load by the frame area of 0.025 m^2. The shear strength measured by this method is called the shear frame index (SFI; Perla et al., 1982). For statistical analysis, 5 - 11 measurements were conducted and the mean, maximum and minimum values were calculated. Sommerfeld (1980), Perla et al. (1982) and Fohn (1987) reported that shear strength decreases as the frame area increases. But, the SFI is used in this paper. Each snow layer was classified by its grain shape according to the International Classification (Colbeck et al., 1990). Depth hoar layers were classified to two groups of ‘faceted crystals’ and ‘cup-shaped crystals’. Temperature and density of the depth hoar layer were measured as well. Density was sampled from 30 mm thick layer including the failure plane.

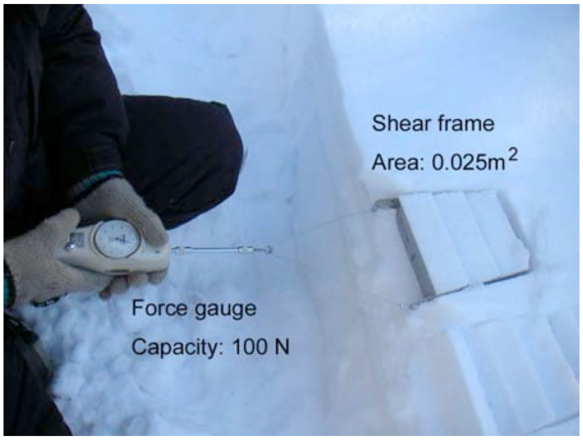

Figure 1: Shear frame and force gauge.

3. SPCIMENS OF DEPTH HOAR

3.1 Natural depth hoar

Many data on shear strength of natural depth hoar layers were collected in four different areas; Sugadaira (24) and Hachimantai (3) in the Honshu Island of Japan, three stations (21) around the Tianshan Mountains in China, and Fairbanks (6) in Alaska, United States. The number in parentheses represents number of data for each area. The shear strength was measured in a flat field, except one case obtained in the Tianshan Mountains. Table 1 shows place, altitude, longitude and elevation for each measurement point. All measurement points are located in cold regions, and exceed 1200 m in elevation except Fairbanks. In Japan, depth hoar is usually observed in plane areas of the Hokkaido Island and high mountainous areas in the Honshu Island (Izumi and Akitaya, 1986). Inland areas around the Tianshan Mountains are identified to the continental weather condition, and depth hoar is typical grain shape in this areas (Qiu, 2004). Fairbanks has a same condition as that of the Tianshan Mountains, but low elevation and high altitude.

Table 1: Place, altitude longitude and elevation of measurement points

Place	Altitude	Longitude	Elevation (m)
Sugadaira Space Radio Observatory, Japan	N 36° 31′ 23″	E 138° 19′ 04″	1,263
Sonntag Hotel, Sugadaira, Japan	N 36° 31′ 27″	E 138° 18′ 52″	1,292
Top of a hill, Sugadaira, Japan	N 36° 31′ 24″	E 138° 18′ 36″	1,324
Omatsu Second Lift, Sugadaira, Japan	N 36° 31′ 11″	E 138° 18′ 56″	1,340
Peak of Mt. Omatsu, Sugadaira, Japan	N 36° 30′ 45″	E 138° 18′ 20″	1,660
Peak of Mt. Ohkuromori, Hachimantai, Japan	N 39° 57′ 34″	E 140° 54′ 56″	1,453
Slope of Mt. Ohkuromori, Hachimantai, Japan	N 39° 57′ 18″	E 140° 55′ 13″	1,301
Ertai Station, Tianshan Mountains, China	N 44° 27′ 00″	E 81° 04′ 47″	1,616
Nalati Station, Tianshan Mountains, China	N 43° 16′ 07″	E 84° 17′ 16″	1,653
Tianshan Station of Snow & Avalanche Research, Tianshan Mountains, China	N 43° 15′ 33″	E 84° 23′ 58″	1,776
Caribou Poker Creek, Fairbanks, United States	N 65° 09′ 00″	W 147° 32′ 36″	258

Figure 2 shows profiles of temperature and temperature gradient of snow obtained in Sugadaira and Tianshan Station of Snow and Avalanche Research. The temperature gradients in Sugadaira were small, hence faceted crystals were observed in snow. In the Tianshan Station, cup-shaped crystals were mostly observed because of large temperature gradients (Figure 3). Grain shape of snow particles of depth hoar layers was carefully classified using 7 X and 20 X magnifiers according to the International Classification (Colbeck et al., 1990).

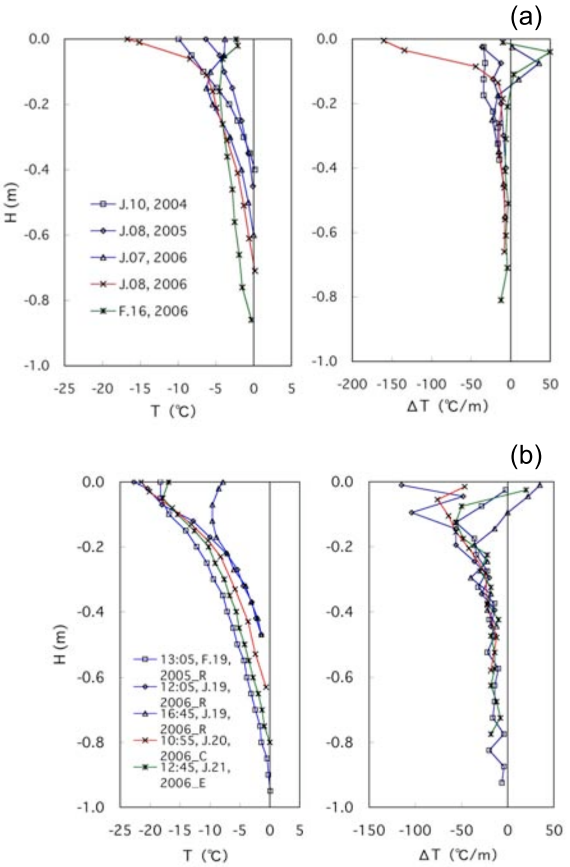

Figure 2: Profiles of temperature (T) and temperature gradient (ΔT) of snow in Sugadaira (a) and Tianshan Station (b). Top represents the snow surface, and lowest one the ground surface.

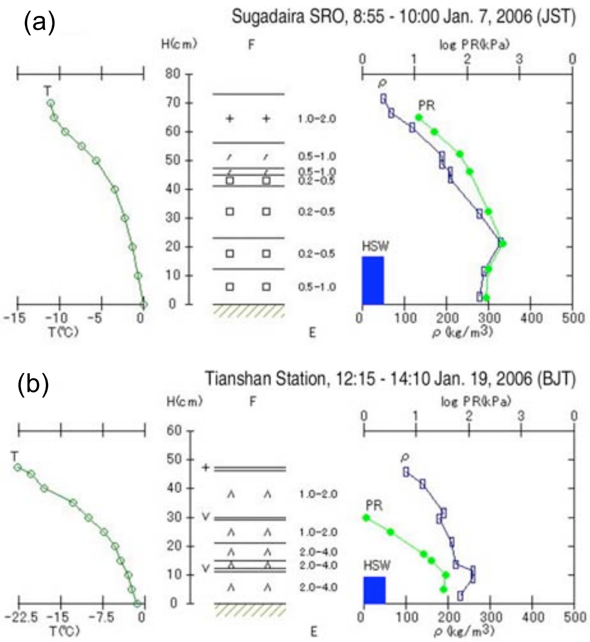

Figure 3: Results of the snow pit observation in Sugadaira (a) and Tianshan Station (b).

F: grain shape, PR: hardness , T: temperature, E: diameter of grains, ρ: density and HSW: water equivalent of snow.

3.2 Artificial depth hoar

Two types of artificial snow particles; dendrites and ice spheres can be produced on an area of 3 X 5 m^2 in the Cryospheric Environment Simulator (CES) (Higashiura et al., 1997). To make depth hoar layers, dendrites are used as new snow on the initial stage, and ice spheres with diameter about 50 μm as rounded grains. Initial densities of the two types of snow are about 30 kg m^{-3} for dendrites and 200 kg m^{-3} for ice spheres. Experiment procedure is as follows (Figure 4):

1) Set insulators (with thickness of 100 mm) on a table (3 X 5 m^2).
2) Set electric plane heaters (5) with a power of 100 W m^{-2} in maximum on the insulators.
3) Set aluminum plates (5) on the electric heaters.

4) Set wood plates (12) on the aluminum plates.
5) Set snow bed (50) on the wood plates.
6) Form snow (~500) on the snow bed.
7) Control air temperature and snow temperature of the bottom.

Some of them the table was kept to be 30 degrees to measure shear strength of snow onto a slope. However when we measure the shear strength of the snow, the table was reverted to be horizontal plane.

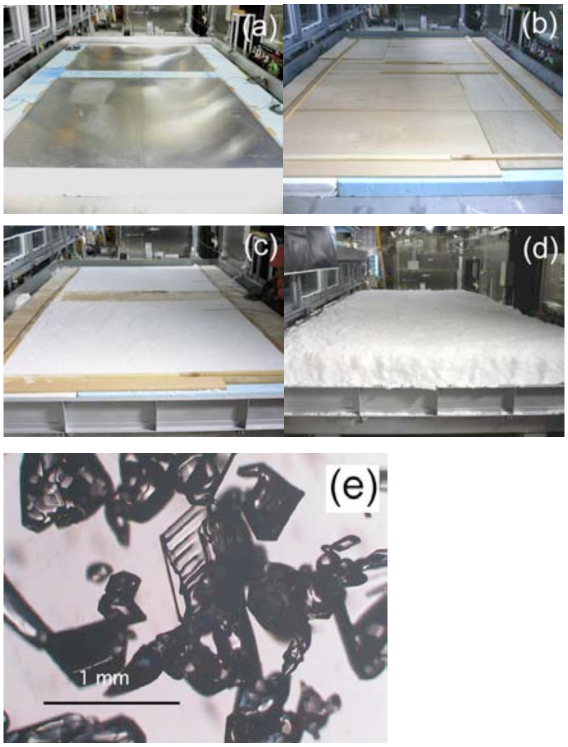

Figure 4: Procedure to make a depth hoar layer in snow. (a): Insulators + heaters + aluminum plates, (b): + wood plates, (c):+ snow bed, (d): + artificial snow, (e): an example of microscopic image of depth hoar particles.

We have made seven experiments for artificial depth hoar layers (Table 2). Air temperature in a cold room was kept a constant of –15 or –10 °C, but for the last one in Table 2, the air temperature was changed from –15 to –5 °C during the period. Temperature of the bottom of snow was controlled to be 0 to –5 °C, so the snow was exposed to steep temperature gradients between –10 - -30 °C m^{-1}. Two days later since the snow cover was exposed to the steep temperature gradient, faceted crystals were usually formed in the snow. Shear strength of the depth hoar layers was measured by the same method as that of the natural snow layers, but the number of shear frame tests was reduced to be 5 – 7 according to the limit space. Grain shapes of snow particles were classified by microscopic images. For example, when faceted crystals more than half number of grains are found in the image, the grain shape is classified to be faceted crystals.

Table 2: List of experiments for artificial depth hoar layers

No.	Period	Days	Type of particles	Air temperature(℃)
1	May 6, 2003 ~ May 15, 2003	10	Dendrite	-15
2	Aug.4, 2003 ~ Aug.9, 2003	6	Dendrite	-10
3	Dec.22, 2003 ~ Jan.4, 2004	14	Dendrite	-15
4	Feb.24, 2004 ~ Mar.8, 2004	13	Ice sphere	-15
5	Apr.27, 2004 ~ May 7, 2004	11	Dendrite	-15
6	Apr.28, 2005 ~ May 9, 2005	12	Dendrite	-10
7	May 1, 2006 ~ May 15, 2006	15	Dendrite	-15 to -5

4. RESULTS

4.1 Natural depth hoar

Mechanical properties of snow are usually related with density. Therefore SFI of natural depth hoar layers has been related to density as shown in Figure 5. Depth hoar layers are classified to two groups of faceted crystals (□) and cup-shaped crystals (△) in according to the International Classification (Colbeck et al., 1990). For comparing to the present measurements, a relation is shown in this figure, which was established by Yamanoi and Endo

(2002) for dry snow under equi-temperature metamorphism just blow the melting point (0°C). SFI of the depth hoar layers has wide variation, and is obviously smaller than that of snow under the equi-temperature metamorphism with the same density. SFI of faceted crystals is slightly larger than that of cup-shaped crystals. With regard to measurement points, SFI obtained in Fairbanks and Hachimantai show slightly smaller than that in the Tianshan Mts. The density which was sampled from 30 mm thick layer including the failure plane, then the values for thin weak layers less than 30 mm are plotted at the higher place on the X-axis. We did not measure the thickness of the weak layers, but about half of the weak layers were less than 30 mm.

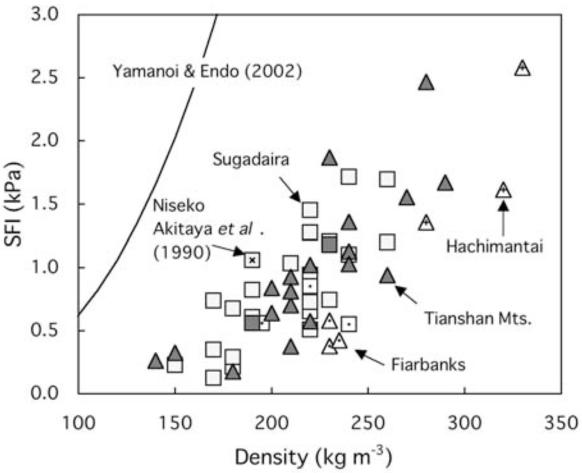

Figure 5 Relation between SFI and density of natural depth hoar layers measured in fields.
The solid line represents the relation for dry snow reported by Yamanoi and Endo (2002). The plot of solid type was measured on a slope in the Niseko Skii Resort, Hokkaido Island (Akitaya et al., 1990).

4.2 Artificial depth hoar with low-density

Snow layers consisted of dendrite particles have low-density at the first stage, and after they were exposed to the steep temperature gradient, changed to faceted and cup-shaped crystals. Time series of the relation between SFI and density is shown in Figure 6. Time series (a) and (b) were obtained at the same run, but (a) was in bottom layer and (b) in upper layer. In the case of (a), grain shapes changed to faceted and cup-shaped crystals as density increased, but in the case of (b), the snow layer kept still low density. Time series (c) and (d) show changing from TG to ET conditions. At first faceted and cup-shaped crystals snow layers were formed by exposing under steep temperature gradients for six days, then the temperature gradient was removed by turnoff the heaters. In the case of (c), cup-shaped crystals in which temperature gradient was about -60 °C m^{-1} at the first stage, changed to faceted crystals. In the case of (d), solid-type depth hoar in which temperature gradient was about -40 °C m^{-1}, changed to rounded grains.

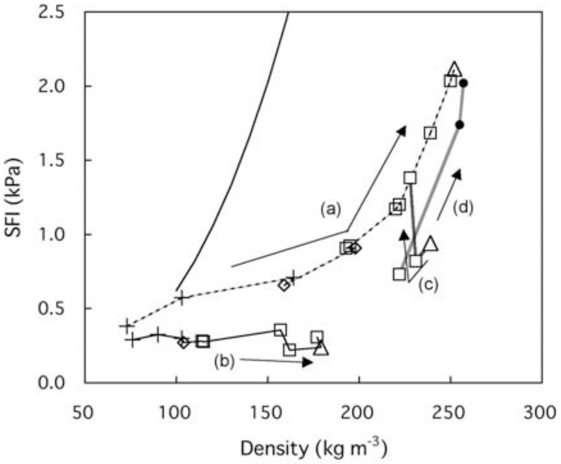

Figure 6 Relation between SFI and density for artificial low-density snow layers.
＋: new snow, ◇: partly rounded snow, ●: rounded snow, □: faceted crystals, △: cup-shaped crystals. The solid line is the same as Figure 5.

4.3 Artificial depth hoar with high-density

Time series for high-density artificial snow layers is shown in Figure 7. Snow layers consisted of ice particles have high density, and its initial grain shape was rounded grains, and they have stepped three different ways depend on the place of the snow, (a): upper (h=30 cm) (b) middle (15) and (c) lower (10) parts. The temperature gradients of the snow were almost same, but different temperatures. The upper and middle snow layers of (a) and (b) were in a low temperature, then the grain shape changed to solid-type, but the lower snow layer of (c) was in a temperature close to the melting point, hence the grain shapes kept rounded grains. Cup-shaped crystals have been not formed in the high-density snow layers.

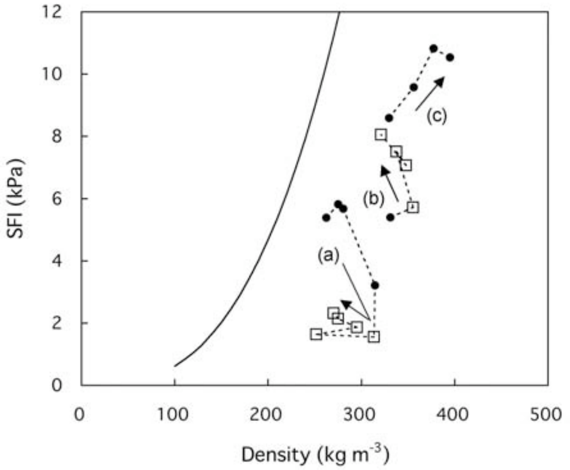

Figure 7 Relation between SFI and density for artificial high-density snow layers.

5. DISCUSSION AND CONCLUSIONS

Figure 8 shows relation between SFI and density of faceted and cup-shaped crystals depth hoar layers. As shown in Figure 8 -(b), there is no difference between the both relations for natural and artificial snow layers. This result suggests that the SFI of both snow layers can be described by an empirical formula. SFI for the faceted crystals had a wide variable range with density, so an exponential equation was proposed using the all of data for the faceted crystals as shown in Figure 8-(a). The relation between shear strength, SFI (in kPa), and density, r (in kg m^{-3}) can be described by an equation as follows:

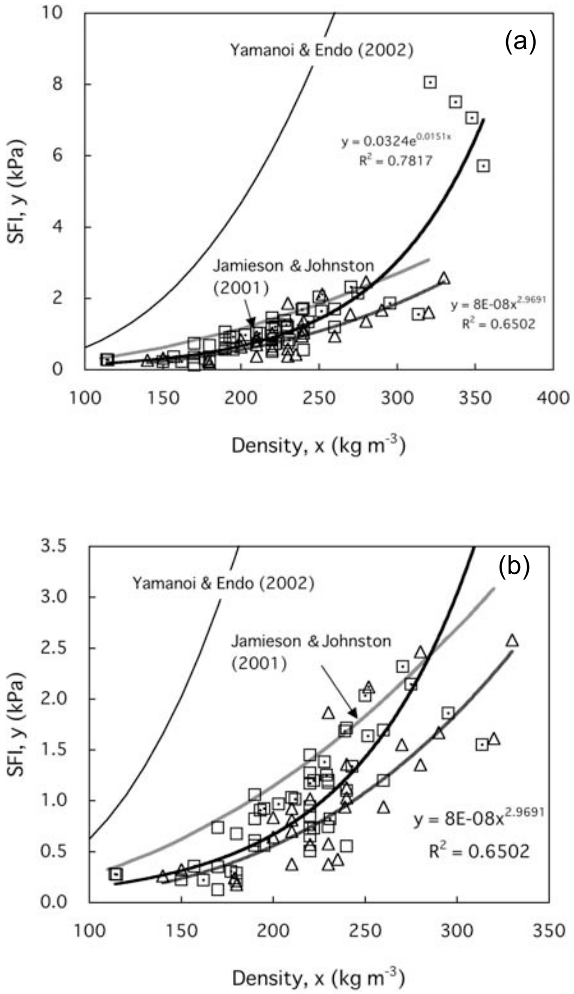

Figure 8 relation between SFI and density of both natural and artificial depth hoar layers. The mark with a dot at the center represents an artificial snow. (b) is the enlarged one of a part of (a).

$$SFI = 0.0324 \exp(0.0151\,\rho) \quad r^2 = 0.78 \quad (1)$$

Akitaya (1972) reported that hardness of high-density snow increases quickly with density higher than 350 kg m^{-3}. This suggests that SFI with high density has also large value. Equation (1) can express SFI until to the high density areas, where avalanches will not occur.

The other hand, the cup-shaped crystals could not be observed at high density more than 350 kg m^{-3}, so different type of equation with Equation (1) is proposed as follows:

$$SFI = 8 \times 10^{-8}\,\rho^{2.9691} \quad r^2 = 0.65 \qquad (2)$$

This equation shows smaller values than that of Jamieson and Johnston's equation (2001). They converted from raw values to the Σ_∞ that is for the shear strength of an arbitrarily large specimen, then the equation reported by them were reconverted to the raw values in this figure. If the present equation is compared to the equation using Σ_∞, these two equations are comparable. Much difference between two equations should be investigated in near future.

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