SLUSHFLOW DISASTERS IN JAPAN AND ITS CHARACTERISTICS

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ABSTRACT: Slushflow or slush avalanches are described as the rapid mass movements of water-saturated snow that most commonly occur during the early part of snowmelt season. In Japan slush avalanches are a major natural hazard on the eastern slope of Mt. Fuji. In spite of recent warmer and less snow winter years some slushflow disasters occurred not only at Mt. Fuji but also in some small rivers at Tohoku and Hokuriku districts. These slushflow disasters were reported.

To study characteristics of slushflow, the measurements of impact force and viscosity of slush were carried out. Our experiments have shown that the slush behaves as "pseudoplastic" of non-Newtonian fluid with coagulational structures.

1. INTRODUCTION

Slush avalanches are rapid mass movements of water-saturated snow and occur every year on the eastern slope of Mt. Fuji in Japan, which causes deforestation near the timberline and natural disaster (Anma et al., 1988). The slush avalanches have primarily been reported from uninhabited arctic (Nobles, 1965) and mountainous regions (Cottman, 1965). In Norway the slush avalanches every year cause damage to men, housings, communication lines and etc.(Hestnes, 1985).

Recently slushflow disasters occurred in some small rivers at Tohoku and Hokuriku districts, Japan, and some people were killed by

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these slushflows, which were first noticed as sulushflow, not debrisflow or flood in these districts.

In order to quantify slushflow problems, physical and mechanical properties of slush must be known experimentally.

2. SLUSHFLOW DISASTERS IN JAPAN

In Japan slush avalanche are a major natural hazard on the eastern slope of Mt. Fuji(Anma et al.,1988). The upper limit of timberline on Mt. Fuji will be at least 2700 m above sea level, however at the eastern slope is lowered down to 1400 m by slush avalanches. In spite of recent warmer and less snow winter years some slush flow disasters occurred not only at Mt. Fuji but also in some small rivers at Tohoku and Hokuriku districts.

The most big slush flow disaster occured in Japan was at Ohzikari, Aomori prefecture on March 22, 1945. At that time, eighty-eight people were killed and twenty houses crushed by the slushflow. Including this slushflow disasters occurred recently in Japan were listed in Table 1. As shown in Table 1, the cause of slushflow is snow mass in the rivers formed by avalanche or blowing snow. This massive accumulation of snow, known as a snow-dam, will obstruct the normal course of stream flow. The decay processes of snow-dam are very important concerning with release mechanism of slushflow. These processes include snowmelt, seepage erosion, down-cutting, snowslope failure and flotation of snow-dam.

Table 1 Slushflow disasters in Japan

No	Date	Place	Cause	Damage
1	Mar.22, 1945	Ajigasawa, Aomori Akaishi River	Avalanche debris	88 killed 20 houses
2	Mar.14, 1981	Makimura, Niigata Iida River	Avalanche debris	1 killed 1 damaged
3	Feb.11, 1990	Tugaike, Nagano Karasawa River	Snow accumulation	2 killed
4	Dec.04, 1990	Matuo, Iwate Akagawa River	Snow accumulation	2 killed
5	Mar.01, 1992	Kurobe, Toyama Kurobe River	Avalanche debris	1 killed 1 damaged

Kobayashi and Izumi (1990) reported a catastrophic slushflow occurred at a small river in the Tugaike ski field, Nagano Prefecture on Febryary 11, 1990. The small river, named Karasawa, is about 5 m wide and 1.5 m deep. The snowpack was filled in the river with floor of the gabion (basket filled with stones) placed up-stream, but there is no snow in the river with concrete floor placed down-stream. Two skiers on the wooden bridge were killed by the slushflow at 14:40 on Feburuary 11. The warm front was coming in Japan Sea on February 11 so that at 14:00 of that day the temperature rose to 4℃, and during the preceding ten hours 78 mm of rain was recorded. The volume of the slush estimated was about 3000 m^3. In the case of this river the floor with the gabion has to improve to the concrete floor.

However the slushflow occurred at Akagawa which was concrete floor, in spite of less snow in the river. Unfortunately snow-dam by blowing snow was formed up-stream so that two people worked in the river were killed by slushflow occurred on December 4, 1990. Always it is very dangerous to be in the rivers even if there is no water in the rivers.

The big slushflow disaster occurred at Kurobe Canyon, Toyama Prefecture, on March 1,1992 and a concrete gravity dam was struck by snow masses, one workman was killed and one injured (Table 1). In sequence along an up-stream valley there are a lot of snow-dams formed by avalanches. During the melt season, the snow-dam at the up-stream end of the sequence is often the first to be filled with water. Then, one by one, a series of reservoir will be formed. When the first snow-dam ruptures, water will be released to the next reservoir to raise its water level suddenly, causing its decay to accelerate. This flood wave cascades down-stream so that a series of dam failure follows (e.g. Xia and Woo, 1992). Therefore it is very important to monitor the water level along the up-stream for a detection of slushflow occurrence.

3. CHARACTERISTICS OF SLUSH

3.1 Density of slush

The slush is defined as water-saturated snow. Figure 1 shows a theoretical relation between the weight ratio of water/snow and the dry

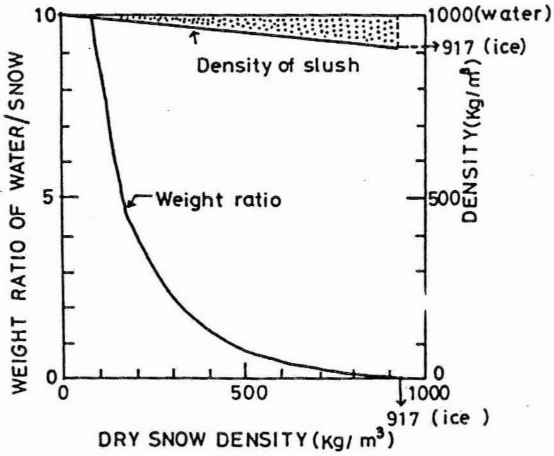

Fig.1 Relation of weight ratio of water/snow to dry snow water/snow

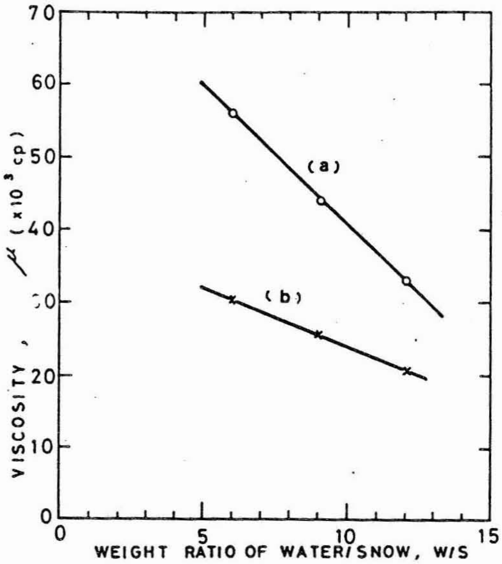

Fig.2 Relation between the viscosity and weight ratio of density, and the region of slush density

(a): shear rate 0.36 S^{-1}

(b): shear rate 0.73 S^{-1}

snow density, and the very narrow region of slush density ranges from 917 kg/m³ (ice density) to 1000 kg/m³ (water density).

In practice it is convenient to use the weight ratio of water/snow in comparison with the density of slush.

3.2 Viscosity of slush

To study characteristics of slush, measurements of the viscosity of slush were carried out by two methods in a 0℃ cold room: a) use of a cylindrical viscometer; and b) measurement of flow along an inclined flat surface. The former method was applied to measure the viscosity under low shear rates between 0.1 and 1.0 S^{-1}. With the latter method the values of viscosity were determined under high shear rates between 25 and 75 S^{-1}.

In the cylindrical viscometer experiments the slush was made by varying the amount of snow weight from 10 to 100 g in 0℃ water, with the total volume of the slush maintained at 500 ml. The measurements of viscosity using this method succeeded with up to 1.0 S^{-1} of shear rate. At a higher shear rate a slip occurred at the boundary between the rotor and the slush. For this reason we used a different method for the high shear rate, i.e., the method of flow along an inclined flat surface was used. The detail of both methods were reported by Kobayashi and Izumi (1989).

Figure 2 shows the relation between the viscosity of slush and the weight ratio of water/snow (W/S) obtained from the viscometer. In the figure, the line (a) is obtained under a shear rate of 0.36 S^{-1} and the line (b) under a shear rate of 0.73 S^{-1}. The viscosity of slush under a higher shear rate showed lower values than those under a lower shear rate. The magnitude of reduction of viscosity under a higher shear rate decreased more slowly than those under a lower shear rate as the ratio of water/snow increased.

A measuring apparatus of moving slush shown in Fig.3 consists of a table that can be inclined and an open channel (width 15 cm) on the table. The channel, made of transparent material, is divided into two parts by a shutter; a slush reservoir and a runoff section. The slush in this experiment was made by mixing 5 kg of water and 1 kg of snow. This method is based on a consideration of shell momentum balance in the fluid flow along an inclined flat surface (e.g. Bird et al., 1960). According to this theory the maximum velocity assumed to be the velocity at the surface is:

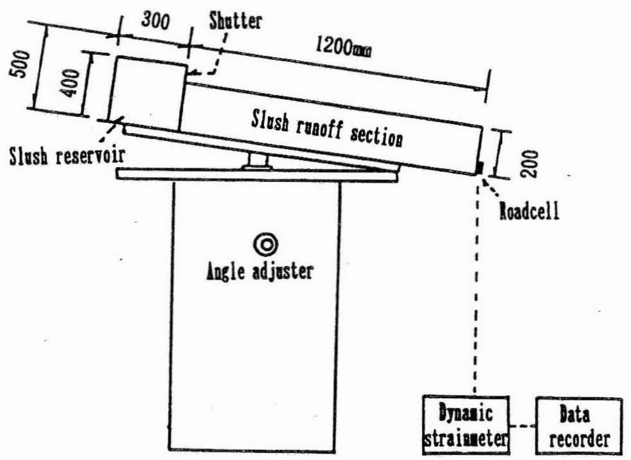

Fig.3 Measuring apparatus for slushflow along an inclined channel

$$V_{max} = \frac{\rho \ g \ \delta^2 \sin\beta}{2 \ \mu} \quad , \qquad (1)$$

where ρ : density of slush, g: gravitational acceleration, δ : thickness of the slush, μ : viscosity, and β : angle of inclination.

To measure the thickness and the surface velocity of the slush, we used a video camera and read the pictures every 1/30 seconds.

We have measured the maximum velocity and the thickness of a slush flow under three inclinations: β = 3, 5 and 10 degrees, as shown in Table 2. Using the values in Table 2 we calculated the viscosity at higher shear rates by equation (1). In Table 2 the values of viscosity, shear rate and shear stress are also included. The shear rate (D) and the shear stress (S) are given by

$$D = V_{max} / \delta \quad , \qquad (2)$$

$$S = \rho g \delta \sin\beta \quad , \qquad (3)$$

where the value of density of slush 950 Kg/m^3 was used for calculations.

To ascertain a flow characteristic of the slushflow, we caluculated the Reynolds number and the Froude number shown in Table 2. The Reynolds

Table 2 Various values obtained from falling slush flow experiment

	Inclination angle (β)		
	3°	5°	10°
Maximum velocity (V_{max}), m/s	1.04	1.24	1.41
Thickness (δ), cm	3.0	2.5	1.9
Shear rate (D), S	34.7	49.6	74.2
Shear stress (S), Pa	14.6	20.3	30.7
Viscosity (μ), cp	2.12	2.04	2.07
Reynolds number (Re)	374.0	385.0	328.0
Froude number (Fr)	1.6	2.8	4.8

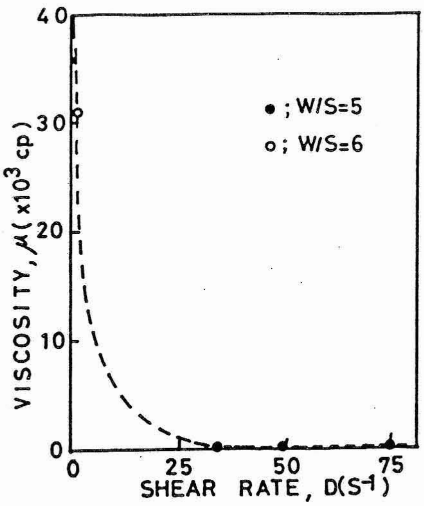

Fig.4 Viscosity of slush as a function of shear rate

○ : viscometer experiment
● : falling slush flow experiment

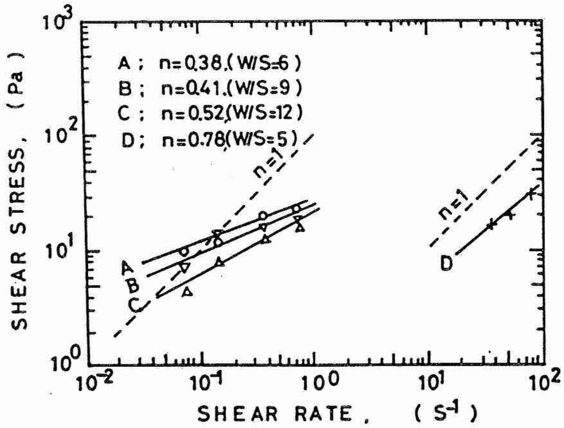

Fig.5 Relation between the shear stress and the shear rate

○,▽,△ : viscometer experiment,
+ : falling slush flow experiment

number shown in Table 2 may give a flow pattern of laminar flow with rippling (e.g. Bird et al., 1960).

By including the data from the viscometer, the viscosity of slush as a function of the shear rate was determined as shown in Fig.4. The figure also shows that the viscosity rapidly decreases with an increasing shear rate. It appears that the values of viscosity to high shear rate give a value close to that for water at 0℃ (1.79 cp). Our experiments have shown that the slush behaves as a non-Newtonian fluid. For materials in which the viscosity decreases with increasing the shear rate, the behaviour is termed pseudoplastic. For pseudoplastic fluids, the power law is appropriate

$$S = \mu D^n \quad , \tag{4}$$

where n is non-Newtonian index of viscosity in which $1>n>0$. According to our results, the values of n were less than unity as shown in Fig.5. As seen in the figure, the values of n approached to the value of Newtonian fluid (n=1) with increasing the shear rate and the weight ratio of water/snow (W/S).

3.3 Impact force of slush

Impact force was measured with a strain guage type pressure transducer (roadcell); its form is a disk of 11 mm in diameter (cross section: 0.95 cm^2). This roadcell was mounted on a L shaped steel bar above the end of sloped chute and data were recorded on a memory recorder as shown in Fig.3.

Figure 6 shows a typical example of impact forces of water-flow and slushflow. The impact force of slushflow showed high-frequency oscillations in the magnitude from 0 to 80 gf. The magnitude of impact force of water-flow is small compared with that of slush as shown in Fig.6. This seems that the slush has a coagulational structure and the scale of coagulation of slush should be large compared with that of the presssure transducer. This structure will be supported by pseudoplastic fluid of slushflow.

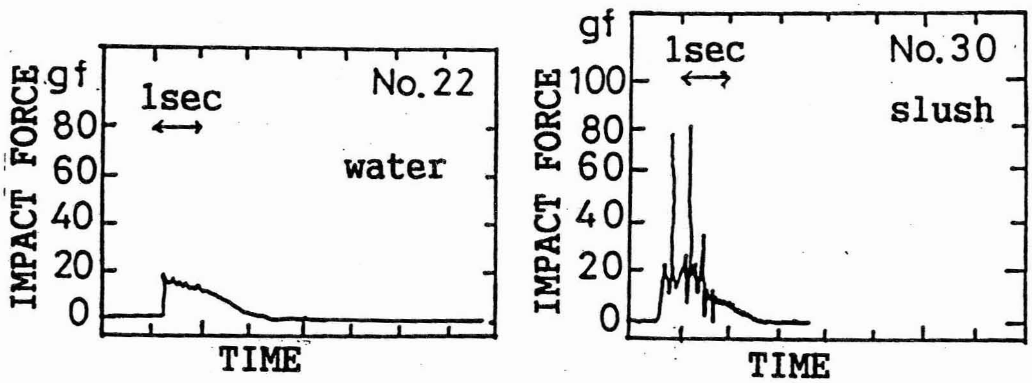

Fig.6 Impact forces of water and slushflow

4. CONCLUDING REMARKS

In this paper, slushflow disasters occurred recently in Japan were discribed, and some physical properties of slush were studied experimentally. Our experiments have shown that the slush behaves as "pseudoplastic" of non-Newtonian fluid with coagulational structures.

The foregoing falling flow theory is valid only when the slush flow is falling as a laminar flow with straight stream lines. For slow and thin viscous film flow, these conditions are satisfied. Although our study is lacking a preciseness, this falling flow method is available in an approximated estimation for the values of slush. Accordingly, the values of viscosity obtained here should be regarded as the apparent values.

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