SIMULATION OF SNOW AVALANCHE BASED ON THIXOTROPY MODEL FOR SNOW-COVERED MODEL

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ABSTRACT: In this research, the CFD-based numerical method for snow avalanche using Bingham fluid model is development. This simulation model has already been confirmed that reproduced to actual avalanche motions. However, it is difficult to reproduced a complete resting state of snow avalanche motions because it is solved using the CFD. For this reason, it is not possible to consider the case such as effect of incorporation snow-covered condition. Therefore, this simulation should be set up excessively large value of snow avalanche on initial area of before flowing. In order to be closer to actual avalanche motions, this model should be additionally high accuracy is required. In this study, we introduced new viscosity model such as thixotropy model for reproduced the resting state with snow-covered condition. It was modeled the result from experiment for the viscosity characteristics on fluidized snow.

In order to validate that effectiveness of proposed model, the flow experiments of artificial avalanche under the model slope was carried out. In the experiment, to confirm the effect of snow-covered conditions it was previously. And then the simulation of experiments was carried out. These results of simulation and experiment has shown that proposed model is possible to reproduce the experimental. For next step, this research plan to reproduce the actual avalanche using proposed model.

KEYWORDS: avalanche, CFD, snow-covered condition, thixotropy.

1. INTRODUCTION

The numerical model uses the Bingham fluid model to describe the complex flow behavior of snow and has been used to reproduce laboratory experiments of submarine slides. The main advantage of these methods is their ability to predict vertical velocity distribution and pressure. This simulation model has already been confirmed that reproduced to actual avalanche motions. But, it is difficult to reproduced a complete resting state of snow avalanche motions because it is solved using the CFD.

In order to be closer to actual avalanche motions, this model should be additionally high accuracy is required. In this study, in order to introduce new viscosity model such as thixotropy model for reproduced the resting state with snow-covered condition, the flow experiments of artificial avalanche under the model slope was carried out. Then, it was modeled the result from experiment for the viscosity characteristics on fluidized snow.

2. EXPERIMENTS

2.1 Snow condiitions

Laboratory experiments were conducted using snow stocked in a room kept at -20°C. This room was made available by the National Research Institute for Earth Science and Disaster Prevention (NIED). All the snow used in laboratory experiment was classified as 'lightly compacted snow'. In the flow experiments of artificial avalanche, snow condition was 'Granular snow'.

2.2 Viscosity of fluidized snow

Fluidized snow behavior was found to be as a Bingham fluid from previous study (Sawada et al. (2015)). But, the behavior of before fluidizing is not discussed in detail. So, in this study, to obtain the behavior of before fluidized. Fig.1 shows characteristic of flowing snow from experimental result using viscometer test. If snow doesn't move or a few move, it condition will becoming like a rigid. Thus, viscosity coefficient of snow will be infinity. But, numerical simulation cannot express infinity

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condition. In this study, new model use limit of minimum shear strain rate (25 1/s) when equivalent viscosity change maximum.

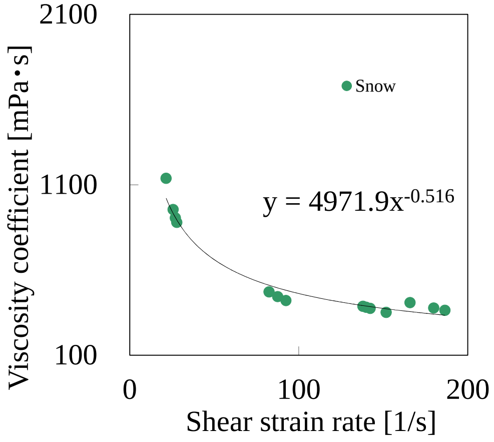

Fig. 1: Experimental result from viscometer test.

2.3 *Shear test of snow with snowpaced-condition*

These can be evaluate the shear stress in the range of static friction, because snow condition becomes like a solid on before fluidized snow condition. In this study, to use condition of before fluidized snow that results of the shear test using snowpacked-condition. These result from previous study (Sawada et al. (2015)).

2.4 *Snow avalanche model testing*

A series of model tests were conducted to measure for snow-covered condition with avalanche. Tests involved a model slope (see Fig. 2). Fig.3 presents the initial position of the snow mass and the dimension of model slope. A triangle prism box was set at the upper section of the model slope; this box was filled with snow and a snow flow was initiated by opening its door. The model slope was 395 cm long and 25.0 cm wide and the bottom of the model slope was coated with artificial grass. If the generated snow produced snow blocks during an avalanche, it would be difficult to maintain reproducibility. To prevent snow blocks from occurring, the snow was first placed in the box and then dropped to the slope. Initial weight of the snow mass is 150 N. The snow block used in these model tests set up snow block on the bottom of slope. These experiments conducted to determine whether or not observed snow-covered condition.

Fig. 2: Overview imager of model slope.

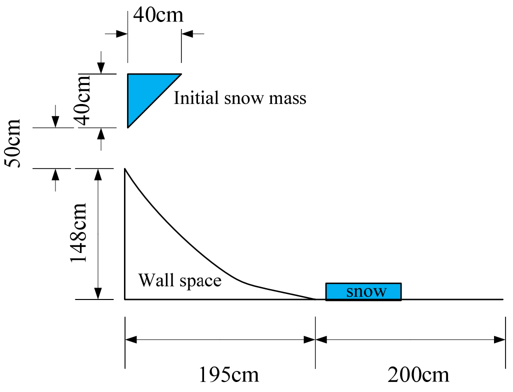

Fig.3: The dimension of model slope.

3. NUMERICAL FRAMEWORK

3.1 *Constitutive model*

Many rheological models have been proposed to describe the behavior of flowing sediment. The Bingham model has been recognized as one of the most versatile model and it is used in this study. In a simple shear state, Bingham model can be described as a linear expression between the shear stress and the shear strain rate as follows,

$$\tau = \eta_0 \dot{\gamma} + \tau_y \qquad (1)$$

where τ is the shear stress, η_0 is the viscosity after yield, $\dot{\gamma}$ is the shear strain rate and τ_y is the yield shear strength. In order to describe both the cohesive and frictional behavior of material, Coulomb's failure criterion is introduced as the yield shear strength for Bingham model. The yield criterion is defined by following equation.

$$\tau = \eta_0 \dot{\gamma} + c + \sigma_n \tan\phi \tag{2}$$

where c is the cohesion, ϕ is the angle of internal friction, and σ_n is the normal stress. Since the snow avalanche is assumed to be fluid, the normal stress can be replaced by the hydrostatic pressure p as shown in the following equation,

$$\tau = \eta_0 \dot{\gamma} + c + p \tan\phi \tag{3}$$

An equivalent viscosity η' can be obtained from the above equation as,

$$\eta' = \frac{\tau}{\dot{\gamma}} = \eta_0 + \frac{(c + p\tan\phi)}{\dot{\gamma}} \tag{4}$$

Equation (4) is determined that the equivalent viscosity becomes infinite as the shear strain reduces to zero. To avoid this singularity, maximum value of the equivalent viscosity was impose from the equation,

$$\eta' = \begin{cases} \eta_0 + \dfrac{(c + p\tan\phi)}{\dot{\gamma}}, & \eta \le \eta_{max} \\ \eta_{max} \quad , & \eta > \eta_{max} \end{cases} \tag{5}$$

where $\eta_{\max}$ is the maximum equivalent viscosity that serves as a penalty parameter. The above equivalent viscosity is used to consider the effect of the evolving shear strain rate on the flow behavior of the material. In two- and three-dimensional stress states, the equivalent viscosity can be generalized as

$$\eta' = \begin{cases} \eta_0 + \dfrac{(c + p\tan\phi)}{\sqrt{2V_{ij}V_{ij}}}, & \eta \le \eta_{max} \\ \eta_{max} \quad , & \eta > \eta_{max} \end{cases} \tag{6}$$

In which

$$V_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) \tag{7}$$

where u_i is the velocity vector. Generally, snow is comprecible material, however, in this study, snow is assumed to be imcompressible material. In this case, stress can be written down as follows.

$$\sigma_{ij} = -p\delta_{ij} + 2\eta' V_{ij} = -p\delta_{ij} + \eta'\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_i}{\partial x_j}\right) \tag{8}$$

3.2 Thixotropy model

In previous model, the maximum equivalent viscosity used 10^{10} mPa□s. So, previous model is not possible to reproduce like resting state of snow when beginning increase shear strain rate. In this study, new model that like thixotropy model use limit of minimum shear strain rate when equivalent viscosity change maximum. Fig.4 shows image of fluid behavior for avalanche. In Fig.4, maximum equivalent viscosity becomes constant value when shear strain rate is lower value. It state is considered as thixotropic (Peder C. F. et al,. (2006)). In this study, lower value of shear strain rate($\dot{\gamma}_{min}$) 25 1/s was used. Fig.5 shows comparison between normal stress and shear stress from shear test of snow (Oda et al. (2011)). Snow condition is solid when it before flowing. Maximum viscosity of snow-covered is calculated from the equation,

$$\eta' = \frac{\tau}{\dot{\gamma}_{min}} = \frac{0.55 \times p + 634}{25} \tag{9}$$

Valuse of equation(9) were experimentally values.

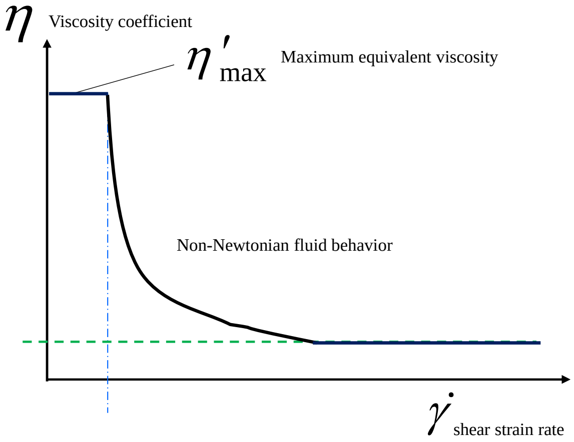

Fig. 4 Image of fluid behavior for avalanche.

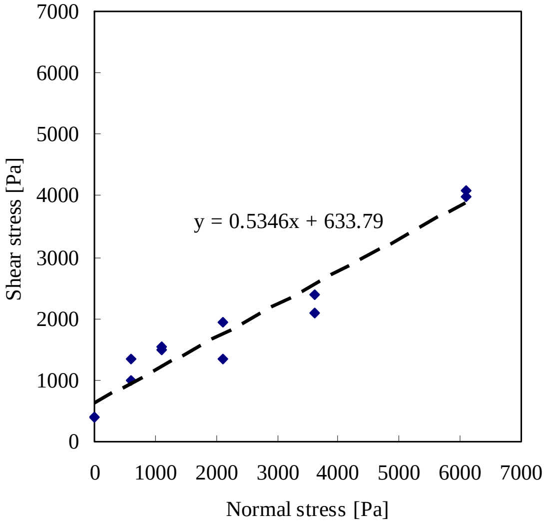

Fig. 5: Normal stress VS Shear stress (shear test of snow).

3.3 Governing equation

The snow is assumed to be an incompressible fluid. The following equations are used as governing equations:

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \frac{1}{\rho}\frac{\partial}{\partial x_j}\left(\eta' V_{ij}\right) + g_i \qquad (10)$$

$$\frac{\partial u_i}{\partial x_i} = 0 \qquad (11)$$

where ρ is the total mass density of the snow and g_i is the gravity acceleration vector. Equation (10) is the linear momentum conservation law. Equation (11) is the equation of continuity. In case of a Newtonian fluid, the viscosity coefficient is constant and its spatial derivative is zero. However, the equivalent viscosity η' has a spatial derivative, therefore equation (10) can be used to incorporate the spatial derivative of η'.

The pressure term, the viscous term and the gravity term are discretized using the finite difference method. The advection term is solved using a confined interpolation profile (Yabe and Aoki (1991)). The pressure is solved implicitly, and the implicit procedure also used to solve the viscous term. As discussed above, equivalent viscosity η' depends on the shear strain rate and calculations must be able to handle very large values. Therefore, it is necessary to use an implicit time integration scheme for the viscous term (Moriguchi et al., (2005)).

The following equation can be used to capture the free surface of flowing snow:

$$\frac{\partial \varphi}{\partial t} + \frac{\partial (u_i \varphi)}{\partial x_i} = 0 \qquad (12)$$

where φ is the volume-of-fluid (VOF) function, initially proposed by Hirt and Nichols (1981). The VOF function is defined at each calculation grid and can have a value from 0.0 to 1.0. The value indicates the occupancy of fluid at each grid. By solving equation (12), it is possible to define the location of the surface implicitly at each time step. In this study, the THINC method (Xiao et al., (2005)) was used to solve equation (12). By using the method, it is possible to conserve the total weight of the VOF function exactly. In addition, the method can maintain the shape of the fluid interface even after many calculation time steps. These advantages are quite important for two-phase flow simulations.

4. SIMULATED SNOW AVALANCHE

4.1 Conditions of numerical analysis

In this simulation, a two-dimensional numerical model was used as based on the model test using slope. Fig.6 shows a numerical model used in the simulation. Snow density was based on the results of the model testing and was set at 500 kg/m^3. Airflow was also incorporated: air density and the viscosity coefficient were set at 1.25 kg/m^3 and 2.00x10^{-5} Pa·s, respectively. Tbl. 1 shows input parameters of snow. The internal friction angle was determined by reference to literatures Oda et al. (2011). A uniform Cartesian mesh was applied in the simulation, using a 1 cm mesh size ($\Delta x = \Delta y$ =1 cm).

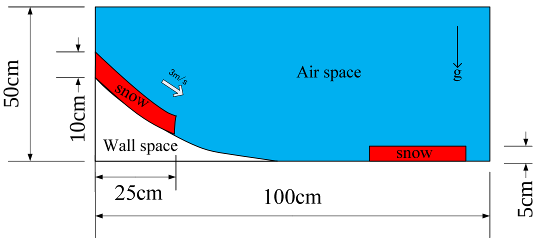

Fig. 6: Numerical model.

Tbl. 1: Parameters of snow

Parameter	*Value*
Density ρ [kg·m^{-3}]	500
Internal friction angle ϕ [degree]	22.0

4.2 Numerical result

Fig.7 presents the result of the simulated model slope test. Fig.8 presents the result of model test. As it can be seen the figures, the result of the simulated model slope test was totally same from the experimental result. On the other hand, it can be summarized that new model can reproduced condition of solid which snow set up on bottom slope.

5. CONCRUTION

In this study, in order to be closer to actual avalanche motions, new viscosity model such as thixotropy model for reproduced the resting state with snow-covered condition was introduced. It was modeled the result from experiment for the viscosity characteristics on fluidized snow. Then, the framework was used to simulation of the model slope test. According to the simulated results, it can be summarized that the new model is effective to snow-covered condition of snow avalanche.

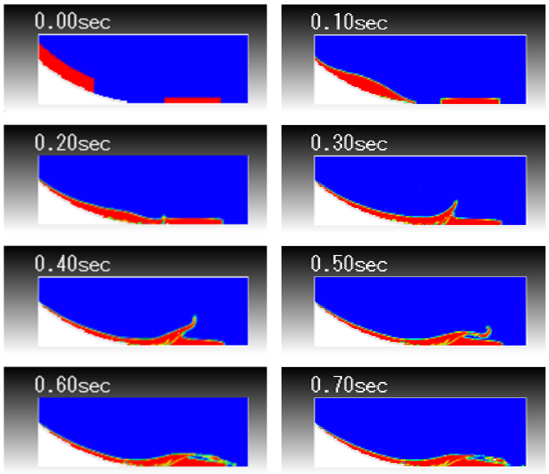

Fig. 7: Simulated result.

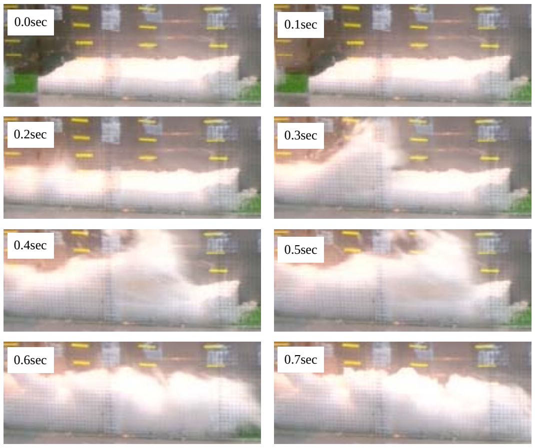

Fig. 8: Result of model slope test.

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