SIMULATION OF AVALANCHE MOTION FOR DESIGN OF SNOW PREDICTION

Kenichi Oda[1]*, Isao Kamiishi[2], Satoru Yamaguchi[2], Yoshihiro Nakamura[3] and Tomio Tanaka[3]

[1]Nihon University, Tokyo, Japan
[2]Snow and Ice Research Center, NIED, Niigata, Japan
[3]Regional Bureau of Hokuriku, Ministry of Land, Infrastructure, Transport and Tourism , Niigata, Japan

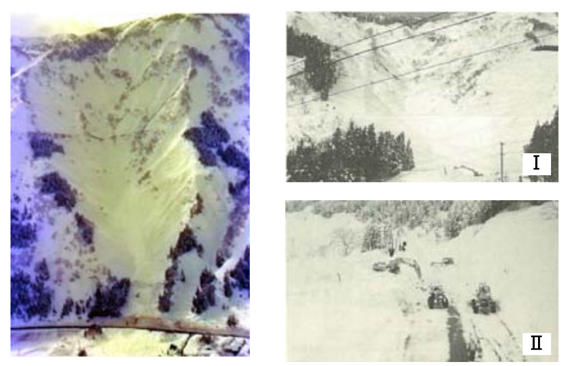
ABSTRACT: The avalanche have potential to cause shut off roads along the railway and inhibiting interregional exchange. Generally, many of the avalanche measures uses analysis from statistics on occurred past avalanches. However, it is difficult to precisely prediction of avalanches because of the avalanche change with terrain condition or condition of deposited snow. Currently, numerical simulations can be useful tools to estimate damage from avalanches. Many tools have been mainly used in Europe and can predict the run-out distance and flow velocity of the avalanche in two and three-dimensional terrain. However, it is difficult for these tools to determine the vertical velocity distribution and pressure under conditions of a dynamic flow because they apply depth-averaged equations. We applied a two-phase flow model to simulate the avalanche motion. The avalanche is modeled as a Bingham fluid. The objective of this study was to validate the applicability of this method to the simulation of avalanches. In this simulation, we reproduced occurrence past avalanche at 1984 in Yuzawa-Horikiri, Yuzawa-cho, Minamiuonuma-gun, Niigata prefecture, Japan. First, we modulated terrain condition data extracted from laser profiler system due to use in this simulation. Next, past avalanche were reproduced in the numerical simulation. Simulated results were compared with reported instance of the avalanche. Finally, we designed the height of deflection fence for avalanche. Simulated result showed that the best height of deflection fence for avalanche is 7.5 m or more.

KEYWORDS: avalanche, numerical framework, deflection fence, three-dimensional simulation.

1. INTRODUCTION

In February 29, 1984, a large avalanche occurred in Horikiri, Itoigawa-shi, Niigata Prefecture, Japan (Nagaoka National Route Work Office, 1989). The avalanche was approximately 10 m wide, 140 m long and 5 m height (total 3,500 m^3 volume) and shutoff the national route for 32 hours and 55 minutes (see Fig 1.). It was caused by heavy snowfall and low temperature run for two days from February 27. Since that time, some protection structures were installed on the slope such as deflecting fences, snow shed and earth mounds. However, these protection structures based empirical method using an avalanche engineer. Therefore, it is not clear yet that these protection structures has depression effect of the avalanche. It is easy to estimate an area which will be damaged from an avalanche by using the empirical method. But the flow velocity, the flow path and the impact force of an avalanche cannot be obtained by using the method. On the other hand, some numerical models had been proposed (e.g. RAMMS (Christen et al., 2002)) for representing a snow avalanche. A lot of numerical results and important knowledge have been reported and discussed based on the numerical models. Those models can describe the flow velocity and the flow path. However, it is difficult to describe an impact

* *Corresponding author address:*
1-8-14, Kanda-Surugadai, Chiyoda-ku, Tokyo Japan, 101-8301;
tel: +81-3-3259-0668; fax: +81-3-3259-0668;
email: oda@civil.cst.nihon-u.ac.jp



(a) Area of the avalanche

(b) I: Condition of after avalanche, II: Clean up the avalanche debris.

Fig. 1: A photo took after the avalanche. (Nagaoka National Route Work Office, 1989)

force and flow behavior on complex geometry because most of the methods are based on the depth-integrated-equations.

In order to overcome the problem mentioned above, this study presents a full three-dimensional simulation of an avalanche. Some researchers had proposed a framework of large deformation analysis of geometrials based on Eulerian type numerical method (Uzuoka et al. (1998), Hadush et al. (2001), Moriguchi et al. (2005, 2009)). In these studies, geometrials are assumed to be the Bingham fluid, and governing equation of fluid is solved. In this study, we performed the full three-dimensional simulation using the same scale avalanche it was occurred in 1984. And then, we discussed whether flow path of the avalanche can be deflected to snow shed from deflection fence for avalanche.

2. NUMERICAL FRAMEWORK

2.1 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,

$$\tau = \eta_0 \dot{\gamma} + \tau_Y \tag{1}$$

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. Because 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,

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

We can see from equation (4) that the equivalent viscosity becomes infinite as the shear strain reduces to zero. To avoid this singularity, we impose a maximum value of the equivalent viscosity from the equation,

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

where η_{max} is a very large number (e.g. 10^{10}) 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

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

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 comprisible material, however, in this study, snow is assumed to be imcompressible material. In this case, stress can be written down as follows.

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

2.2 Governing equation

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

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \frac{1}{\rho}\frac{\partial}{\partial x_j}\left(\eta' V_{ij}\right) + g_i \tag{9}$$

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{10}$$

where ρ is the total mass density of the snow and g_i is the gravity acceleration vector. Equation (9) is the linear momentum conservation law. Equation (10) 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 (9) 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 (CIP; 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:

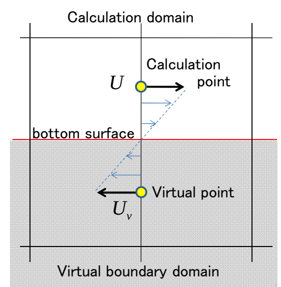
$$\frac{\partial \varphi}{\partial t} + \frac{\partial (u_i \varphi)}{\partial x_i} = 0 \tag{11}$$

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 (11), 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 (11). 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.

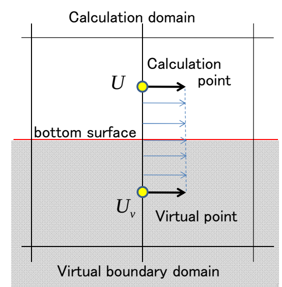
A numerical technique had been proposed to describe the effect of basal friction (Moriguchi et al., 2010). Generally, the non-slip boundary condition is described by setting the velocity vector in the opposite direction in a virtual calculation domain, as shown in Fig. 2 (a). In contrast, Fig. 2 (b) shows that the slip boundary condition can be expressed by setting the velocity vector at the same intensity at the virtual calculation point. To accommodate the effects of basal friction, parameter α, a reduction coefficient of basal friction, is applied. The velocity at the virtual calculation point U_v can be calculated using following equation:

$$U_v = -U(2\alpha - 1) \tag{12}$$

where U is the velocity at a neighboring point in a calculation domain. The non-slip boundary condition and the slip boundary condition are expressed by α=1.0 and 0.0, respectively. By changing the value of α from 0.0 to 1.0, it is possible to describe an arbitrary basal friction angle.



(a) Non-slip boundary condition



(b) Slip boundary condition

Fig. 2: Boundary condition of the velocity.

3. SIMULATED SNOW AVALANCHE

3.1 Conditions of numerical analysis

In this simulation, a three-dimensional numerical model was used as based on the surface model which converted from raster data of Yuzawa city planning map and survey data. Fig. 5 shows a surface model used in the simulation. A mesh size of initial numerical model was 1 m (X=1 m, Y=1 m, Z=1 m).

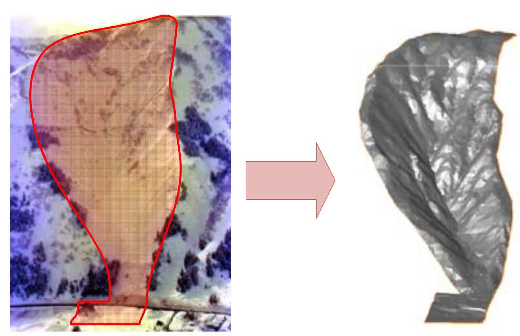
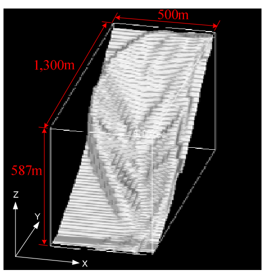
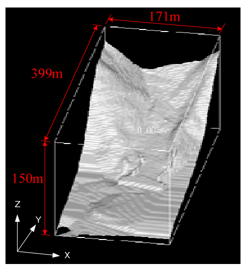


Fig. 3: Area of the avalanche and Surface model.

The numerical framework need high spec calculation memories. If numerical model was large, a calculation time will be longer. In this simulation, it is aimed at large avalanche. Moreover, a limit number of numerical mesh is about 2,000,000. If used an initial numerical model, a simulation will not calculate. Therefore, to assess the effect of the avalanche flow path, the mesh size of a first numerical model was applied in the simulation, using a horizontal direction and a vertical direction were 20 m and height direction was 1 m. And then, using obtained result from a first numerical model, determine the area required for discuss an effectiveness of deflection fences for avalanche. A secondly numerical model was applied in the simulation, using a horizontal direction and a vertical direction were 3 m and height was 1 m. Fig. 4 (a) shows a numerical model used in a first simulation and Fig. 4 (b) shows a numerical model used in a secondly simulation.



(a) Numerical model used a first simulation



(b) Numerical model used a secondly simulation

Fig. 4: Numerical models.

Tbl. 1 shows input parameters of snow. The density was determined based on the report, and other parameters were determined by reference to literatures (Japan Construction Mechanization Association (1988) and Oda et al. (2011)).

Tbl. 1: Parameters of snow

Parameter	*Value*
Density ρ [kg·m^{-3}]	500
Internal friction angle ϕ [degree]	22.0
Cohesion c [Pa]	100
Reduction coefficient of basal friction α	0.70

According to a report of the snow avalanche (Nagaoka National Route Work Office, 1989), maximum and averaged snow depth are 3.0 m, respectively. Therefore, the initial snow depth was set at 3.0 m for a first numerical model. Additionally, two types of initial snow depth were set for a secondly numerical model. One type used same volume as first numerical model (hereinafter referred to as a full volume model). Another type used half volume as first numerical model (hereinafter referred to as a half volume model).

3.2 Numerical result of a first simulation

Fig. 5 shows the simulated result used a first numerical model. In the simulation, the avalanche flowed down along the slope, and stopped area of deflection fences for avalanche. Based on the obtained the result, a secondly numerical model were determined. Fig. 6 shows a secondly numerical model area based on the result of a first simulation.

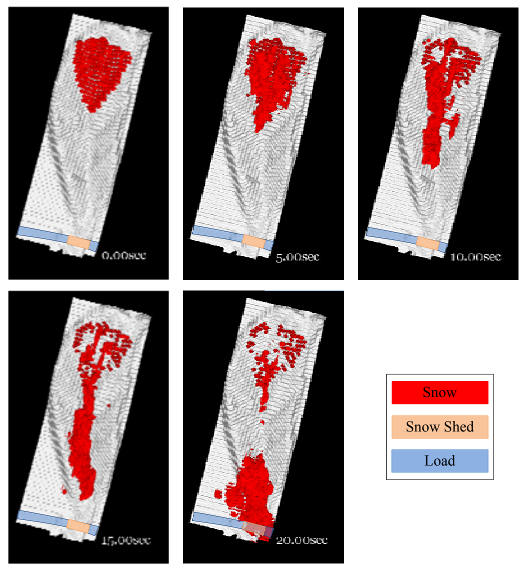


Fig. 5: Simulated result. (using a first numerical model)

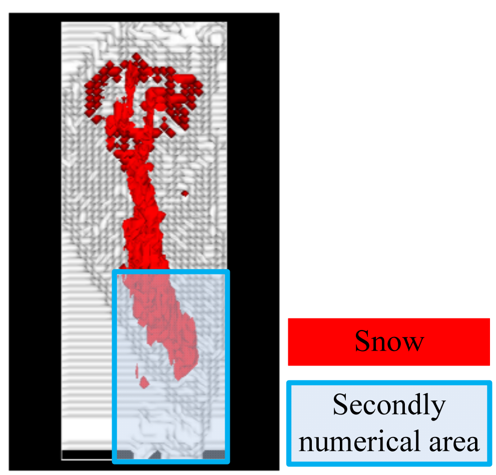
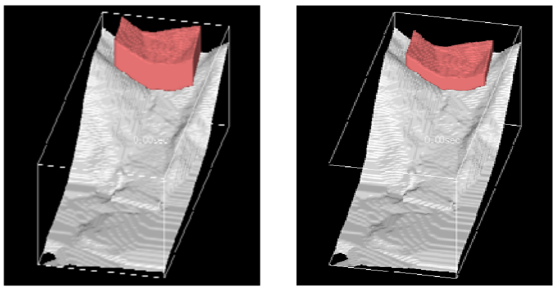


Fig. 6: An area of a secondly numerical model.

3.3 *Numerical result of a secondely simulation*

Fig. 7 shows a secondly numerical model used in this simulation. Moreover, seven types of a height for deflection fence was used in steps of 1 m from 0m to 6 m. A total calculation cases were 14 cases. Fig .8 shows an installation condition of deflection fence for avalanche.



(a) full volume model (b) half volume model

Fig. 7: Installment condition of initial snow. (using a secondly numerical model)

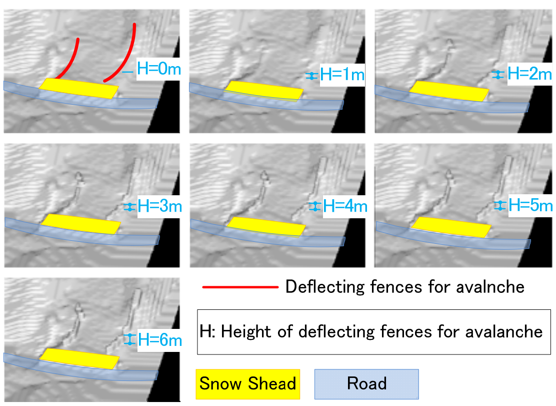


Fig. 8: installation condition of deflection fences for ava-lanche.

Fig.9 shows the simulated result used the full volume model. In the simulation, there has been confirmation of overflow to avalanche on the deflection fence for avalanche. Additionally, the upstream of a left side deflection fence for avalanche wasn't protect the avalanche flow. As a result, an existing deflection fence for avalanche cannot control the avalanche motion into the snow shed.

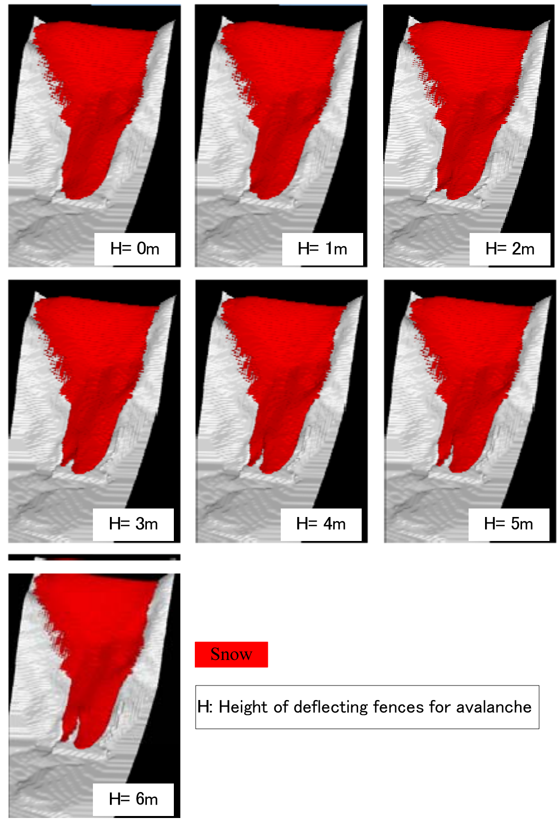


Fig. 9: Simulated results. (using the full volume model)

Fig.10 shows the simulated result used the full volume model. In the simulation, there has been confirmation of overflow to avalanche on the deflection fence for avalanche when a height of deflection fence was less than 3 m. Fig. 11 shows the enlarged result more detail understanding as an effectiveness of the deflection fence. As it can be seen the figure, the deflection fence works well in case that a height is set at 5 m or more. Additionally, actual snow depth was 1 m or more. For this reason, the best of height is 7.5 m or more. However, the upstream of a left side deflection fence for avalanche wasn't protect the avalanche flow.

In addition, it is reasonable that the half volume model is realistic because of It can be seen the result from first simulation that the avalanche volume is about half when the avalanche flowed in the deflection fence area. Moreover, the avalanche will not flow in the left side of deflection fence, because of its area are densely forests and it will protect flow the avalanche.

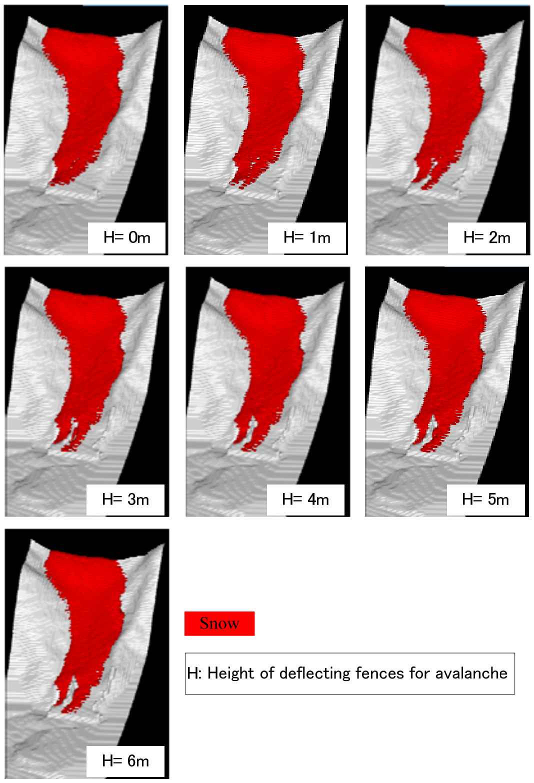


Fig. 10: Simulated results. (using the half volume model)

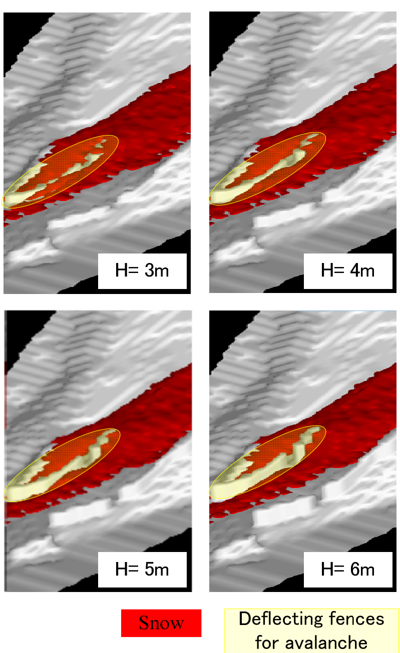


Fig. 11: Enlarged result about effect of deflection fence.

4. CONCRUTION

A numerical framework of large deformation analysis of geomaterials was applied to simulate a snow avalanche which has happened in 1984. The framework was used to simulation of the avalanche. According to the simulated results, it can be summarized that the numerical framework is effective to predict flow behavior of the avalanche. In addition, most effective height of deflection fence for avalanche is 7.5 m or more.

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