論 文 の 内 容 の 要 旨

論文題目　A Bingham Snow Model for Train Safety Using the Moving Particle Semi-Implicit Method
（列車安全のためのMPS法を用いたビンガム雪モデルの研究）

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1. Introduction

Rail transportation is a crucial infrastructure to establish sustainable economy and build global society. In order to respond to the expected growth in transportation demand, both for passenger and freight, many countries continue their efforts to build a railway system with reliability, availability, maintainability and cost efficiency. Safety is a basic and fundamental value to govern the rail system. Neglecting safety with an unsafe railway will lead to economically, environmentally and socially inacceptable consequences.

The purpose of this study is to develop a snow model emphasizing the impact force acting on the train surface to ensure safe driving. A Bingham numerical model is proposed by using the Moving Particle Semi-Implicit (MPS) method and tested for collision between a train and snow. As well, verification of this special non-Newtonian fluid is carried out and good agreement is obtained by comparing the MPS numerical result with a reference solution. Furthermore, two validations, slip condition validation and impact force validation are also implemented, in which results are compared by introducing the present Bingham snow model and the basal friction coefficient. Finally, the time history of impact force in the foremost area of the train head, on the bottom surface of the carriage and on the side surface of the balise is analyzed, which provides a reference for safe driving analysis.

2. Snow simulation

2.1 MPS method

Snow has been modeled by different kinds of numerical methods. They are generally classified into four kinds: fluid models [1], current models [2], mass center models [3] and particle flow models [4]. The Moving Particle Semi-Implicit (MPS) method [5-7] used in this research is categorized as a fluid model. It is a meshless Lagrangian approach which can efficiently simulate large deformations of fluid surface, such as wave breaking phenomena, large plastic deformation problem etc. Additionally, it conforms well to the mass conservation law and there is no numerical diffusion when discretizing the convection terms. Therefore, it has been increasingly applied to a wide variety of physics simulations.

When a train runs over or into a snow-covered track at a high speed, the severe collision between train and snow could cause large impact force that damages the carriage or derails the train. In this case, the behaviors of snow involves large deformation issues. Due to the outstanding advantages of the MPS method, it is very appropriate to simulate snow.

2.2 Snow model

Several fluid models have been adopted for simulating the constitutive behavior of fluidized snow: Bingham fluids [8], Newtonian fluids [9] or Cross fluids [10]. The Bingham fluid was chosen in this study. According to the experiment made by Oda [11], the viscosity is very high when snow is at low shear rates. If the shear rate is increased, its viscosity quickly decreases. This behavior is similar to a Bingham fluid behavior. Therefore, snow is assumed to be a Bingham fluid due to its peculiar shear thinning.

Based on the Bingham model, the Mohr-Coulomb failure criterion is also introduced into the numerical model. This two-dimensional incompressible model takes the form of an equivalent viscosity in order to represent the relationship between shear stress and shear rate of snow and a maximum viscosity is set to avoid calculation failure.

3. Verification

For verification, the proposed Bingham snow model by using the MPS method is applied to a simple problem and compared to the result of the FDM solution. The problem is an x-y two-dimensional Poiseuille flow. In this case, the free flow moves along the x-axis. To evaluate the reference solution and compare it with the MPS method, a finite difference calculation is carried out. Good agreements with the MPS results to the reference solution of the velocity distribution, shear rate and kinematic viscosity are obtained.

4. Validation

4.1 Validation of slip condition

The created Bingham snow model is used to simulate the flowing snow test described in Dent and Lang [12]. The test decelerates snow from 17 m/s to rest. To allow the snow to initially be a single block of material moving at constant speed, the slip boundary condition extends from the leftmost side of run-out zone to the 8 m mark. From there onward is no-slip boundary condition. The yield kinematic viscosity coefficient and maximum kinematic viscosity coefficient are adjusted to make the computed flow conform to the observed motion of the test. It is found that when these two parameters are set as 0.00002 m^2/s and 0.1 m^2/s respectively, the simulation results fit the test data well. The comparing result of the velocity during 0.1-0.2 seconds shows an obvious velocity gradient region near the wall and a nearly uniform flow for the upper part of this snow flowing.

4.2 Validation of impact force

To clarify whether the verified Bingham snow model can properly reproduce the impact force measured in a test, two-dimensional numerical simulations are conducted based on the proposed Bingham snow model. Snow is first gathered in a box and then dropped on the slope from a 3.2 m height. The initial weight of snow is 45 kg. In this simulation, a rotation matrix is adopted to reduce the unnatural splashing phenomenon and a coefficient α is introduced to control the effect of basal friction. The simulation results can fit the experimental data reasonably well. However, treatment of impact force fluctuations when snow starts to strike the measurement equipment is still an unresolved issue. Overcoming this problem requires an improvement of the pressure calculation in MPS simulation.

5. Demonstration

5.1 Low speed collision simulation

The author intends to show the different splashing phenomenon between the proposed Bingham snow model and the low-viscosity Newtonian snow model by simulating a low speed collision between a train and snow. The train passes through the snow block with a constant velocity of 8 m/s. Comparison results show that the Bingham snow model produces a more real snow splashing phenomenon.

5.2 High speed collision simulation

Based on the above low speed collision simulation, a balise and two rails are added into the high speed collision simulation. The constant speed of the train increases to 83 m/s to represent the high speed train. The impact force acting on the front carriage of train are analyzed for the derailment issue and a trial simulation by using the COMSOL is implemented for the balise damage issue. The von Mises stress cloud chart indicates that portion of the balise ruptures and a large deformation occurs under the effect of the average impact force, which is generated because of the continually strike of the snow particles. However, additional experiments are needed to give trust to the data obtained in the high speed collision simulation.

References

[1] Barbolini, M., Gruber, U., Keylock, C. J., Naaim, M., Savi, F., Application of statistical and hydraulic-continuum dense-snow avalanche models to five real European sites, Cold Regions Science and Technology, 2000, 31(2): 133-149.

[2] Hopfinger, E. J., Snow avalanche motion and related phenomena, Annual Review of Fluid Mechanics, 1983, 15(1): 47-76.

[3] Koçyiğit, Ö., Gürer, I., Effect of the voellmy coefficients on determining run-out distance: a case study at uzungöl, Turkey, Gazi University Journal of Science, 2007, 20(3): 79-85.

[4] Takahashi, T., Tsujimoto, H., Granular flow model of avalanche and its application, Journal of Hydroscience and Hydraulic Engineering, 1999, 17(1): 47-58.

[5] Koshizuka, S., Oka, Y., Moving-particle semi-implicit method for fragmentation of incompressible fluid, Nuclear Science and Engineering, 1996, 123(3):421-434.

[6] 越塚誠一，粒子法，丸善出版社, 2006.

[7] 越塚誠一，柴田和也，室谷浩平，粒子法入門，丸善出版社, 2014.

[8] Dent, J. D., Lang, T. E., A biviscous modified Bingham model of snow avalanche motion, Annals of Glaciology, 1983, 4: 42-46.

[9] Norem, H., Irgens, F., Schieldrop, B., A continuum model for calculating snow avalanche velocities, IAHS Publ, 1987, 162: 363-379.

[10] Kern, M. A., Tiefenbacher, F., McElwaine, J. N., The rheology of snow in large chute flows, Cold Regions Science and Technology, 2004, 39(2): 181-192.

[11] 小田憲一，雪崩の挙動予測を目的とした数値解析手法の高度化，岐阜大学博士論文, 2011.

[12] Dent, J. D., Lang, T. E., Experiments on mechanics of flowing snow[J], Cold Regions Science and Technology, 1982, 5(3): 253-258.

[13] Oda, K., Moriguchi, S., Kamiishi, I., Yashima, A., Sawada, K., Sato, A., Simulation of a snow avalanche model test using computational fluid dynamics, Annals of Glaciology, 2011, 52(58): 57-64.