Simulation of Snow-Structure Interaction Using Smoothed Particle hydrodynamics (SPH)

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1. Abstract:

In this paper, an attempt is made to develop a model of snow using the Smoothed Particle Hydrodynamics (SPH) method in LS-Dyna to predict the structural damages caused by snow during various scenarios, such as avalanches and vehicle crashes into piled-up snow heaps. SPH is a particle-based method that uses a Lagrangian approach. It is utilized in LS-Dyna for modeling landslides, fluid dynamics, and geotechnical applications, such as the behavior of snow in avalanches and its interaction with structures. Snow exhibits brittle behavior under certain conditions, a characteristic essential for understanding its interaction with structures. Therefore, for material modeling, we used the Mohr-Coulomb model (MAT 173), which characterizes the material properties of snow using parameters such as Young's Modulus, Poisson's ratio, cohesion, and friction angle. We validated our model by comparing it with a hardware drop test conducted at -2°C and -14°C, where a cylindrical indenter was dropped into a container filled with snow. The simulation results closely matched the hardware test, with a 90% agreement in the measured indentation depths, demonstrating the model's accuracy and reliability.

2. Introduction:

Snow is nothing but a solid form of water composed of ice crystals, these crystals are formed when water vapor in atmosphere condenses directly into a solid state – a process known as deposition. This phenomenon usually happens when the temperatures are below the freezing point of water (i.e., 0°C). The formed ice-crystals link together through hydrogen bonds to form snowflakes, which eventually settle on the ground. This freshly deposited snow has a density less than 100kg/m^{-3}; it then undergoes trough metamorphism due to the wind, variation of daily temperature etc. resulting in change of density from 100kg/m^{-3} to 500kg/m^{-3}. If there is new deposition of snow over the previously deposited snow, the density may change to values greater than 900kg/m^{-3} (i.e., transforms to ice) over a period.

Given the physical properties of snow, several natural disasters can occur, such as avalanches or vehicle crashes into a piled-up snow heaps, this could lead into significant loss of life and property damage. To reduce these damages, it is essential to design systems that can minimize the damages caused in such scenarios. To do it we need to have models which can predict damages in such scenarios, this can be done achieved either through physical experiments or by using a simulation model. However, physical experiments are costly, and since snow is seasonal, it is not always possible to conduct experiments year-around. Therefore, using a simulation model is an efficient method to predict these damages.

In the past, many researchers have attempted to develop computational models for snow, employing various methods. For instance, John Gauem, Jerome Johnson, and others have explored Discrete Element Method(DEM), which, while effective, comes with a significant computational cost, making it challenging to implement for complex problems. Pascal Hagenmuller and his team have used the Finite Element Method (FEM), but FEM struggles with large deformations where mesh distortion can occur.

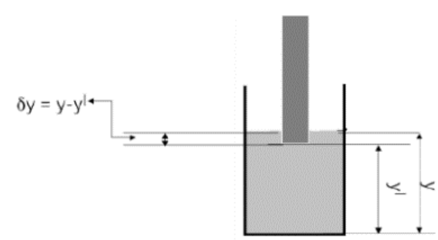
With advancements in computational power, a new class of mesh-free methods have been developed, like Smoothed Particle Hydrodynamics (SPH), Element Free Galerkin (EFG) Method, Diffuse Element Method (DEM). Among these, SPH has gained most popularity and is widely used. It is a mesh-free Lagrangian method originally developed by Lucy, Gingold, and Monaghan to solve astrophysical problems in 3D space. In this paper, we use SPH method to address the challenges associated with the computational time required by DEM and the mesh distortion issues in FEM when modeling snow.

The following sections Experimental Conditions, Modeling of Snow, Results and Discussion provide a detailed explanation of how snow is modeled using SPH and its validation against a Drop test.

3.1 Experimental Conditions:

In our study, we conducted a drop test. In this test, a cylindrical indenter is dropped from a specific height into a cylindrical container filled with freshly deposited snow. We would be measuring the how deeply the indenter has penetrated the snow. The snow was collected at two different temperatures of -2°C and -14°C and is filled into cylindrical container with a diameter of 30cm and height of 50cm, The cylindrical indenter used for the test had a diameter of 7cm and a length of 8cm, these dimensions of the cylindrical indenter were chosen carefully to ensure that its diameter is smaller than the container's diameter, to minimize the possible confinement effects. The container was filled with snow to a depth of 20cm, ensuring a sufficiently deep snow bed for the test. The drop height of the indenter was selected so that It would penetrate to a depth of approximately 10cm into the snow. This was intended to provide a clear observation of the indenter accumulating a densified snow zone beneath it. The experimental conditions were based on the guidelines provided by Daisy Huang and John H. Lee.

Indenter Height	8cm
Indenter Diameter	7cm
Indenter Material	Aluminum
Drop Height	20cm
Simulation Predicted Depth	7.2cm



The above image depicts the experiment setup.

3.2 Model Development:

This section is divided into two parts: Smoothed Particle Hydrodynamics and Model implementation. The first part explains the theoretical background of SPH Method, while second part explains about model development in LS-DYNA.

3.2.1 Smoothed Particle Hydrodynamics (SPH):

Smoothed Particle Hydrodynamics (SPH) is a mesh-free lagrangian method, here algebraic equations are solved systematically across the domain of the problem, unlike relying on a mesh for domain discretization as in the Finite Element Method (FEM). In SPH, a set of nodes are defined throughout the field of interest to establish the boundaries. Mesh-free methods can be categorized based on their formulation. For instance, weak form methods include techniques like Element Free Galerkin (EFG) method and the Meshless local Petrov-Galerkin (MLPG) method. Strong form methods include SPH and collocation method, while strong-weak form methods include approaches like the Moving Least Squares (MWS) method.

The governing equation for SPH, which is available in the LS-Dyna manual is as follows[13]

$$f(x) = \int_{\Omega} f(x`)W(x - x`, h)\, dx`$$

Where h is the smoothing length i.e. the length over which the kernel function has an influence and W(x-x`,h) is the smoothing function which must satisfy the conditions like normalization condition, delta function property and compact condition. Using the SPH formulations the PDE for the motion of particles representing snow is represented as.

$$\frac{D\rho_i}{Dt} = \sum_{j=1}^{N} mj(v_i^{\alpha} - v_j^{\alpha})\frac{\partial W_{ij}}{\partial x_i^{\alpha}}$$

$$\frac{Dv_i^{\alpha}}{Dt} = \sum_{j=1}^{N} mj(\frac{\sigma_i^{\alpha\beta}}{\rho_i^2} + \frac{\sigma_j^{\alpha\beta}}{\rho_j^2})\frac{\partial W_{ij}}{\partial x_j^{\beta}} + f^{\alpha}$$

Where α, β represent the Cartesian components x, y and z with the Einstein convention applied to respective indices, ρ is the density, v is the velocity, $\sigma^{\alpha\beta}$ represent the stress tensor, f^{α} represents the external forces and $\frac{D}{Dt}$ is the material derivative. The strain rate tensor and the rotation rate tensor for the ith particle can be calculated as:

$$\dot{\varepsilon}_i^{\alpha\beta} = \frac{1}{2}(\nabla v_i^{\alpha\beta} + \nabla v_j^{\beta\alpha})$$

$$\omega_i^{\alpha\beta} = \frac{1}{2}(\nabla v_i^{\alpha\beta} + \nabla v_j^{\beta\alpha})$$

By using the above equation, the deviatoric stress components are calculated and the plastic flow is determined by Mohr-Coulomb failure criteria and the deviatoric shear stress of snow are scaled back to maximum shear stress defined by S = c + N$\tan\phi$ Where S is shear stress, c is cohesion and φ is the internal angle of friction of snow. At this stage, the solver ls-dyna uses predictor-corrector algorithm to update the particle position, velocity, density, stress tensor at each time step.

3.2.2 Model Implementation: The experiment contains three main components: a cylindrical container, cylindrical indenter, and the snow. The development and implementation of the computational model for these components are explained below.

3.2.2.1 Element Model:

The computational model was developed using ANSA. The cylindrical container was modeled using 2D elements. The cylindrical indenter was modeled using 3D elements. The snow was modeled using the

Smoothed Particle Hydrodynamics (SPH) method, which can be done using the tank option in ANSA. The following table summarizes the information of model.

Component	Modeling Method	Number of Element (Type)	
Cylinder	2D Elements	6048 (Quad)	72 (Triangular)
Indenter	3d Elements	1430 (Hexa)	10 (Penta)
Snow	SPH	2201368 (SPH)	

3.2.2.2 Material Model:

For the computational model, different material models were used for cylindrical container, cylindrical indenter, and the snow. The material properties for these components are summarized as follows:

Cylindrical Container and Indenter: MAT24 - MAT_PIECEWISE_LINEAR_PLASTICITY is used as a material model. The following table summarizes the properties values used.

Density	7.796E-6 kg/mm-3
Young's Modulus	210 GPa
Yield Stress	200 MPa
Poisson's Ratio	0.3

Snow: MAT110 - MAT_MOHR_COULOMB is used as a material model for Snow.

Density	490E-7 kg/mm-3
Young's Modulus	50 GPa
Poisson's Ratio	0.2
Friction angle	20∘
Cohesion Value	750 Pa
Dilation angle	-30∘

3.2.2.3 Functional Card:

LS-DYNA is used as solver or the computational model and hence some of the following functional cards are necessary in the calculation:

Contact: An automatic node to surface card is used to define contact between SPH(Snow) and the container, Indenter.

Control:

*Control_Energy – It is used to output the energy values in the simulation,

*Control_MPP_Decomposition_Distibute_SPH_Element – Using Multiprocessor

*Control_SPH - Form 12 a moving least-squares based formulation is used for calculation, IDIM 3 is used to solve the problem in 3D.

3.3 Results:

In this paper, we focus on the test, where an indenter was dropped from a height of 20cm into a container filled with snow to a depth of 24cm. The experiment was conducted at two different temperatures, -2°C and -14°C, under varying conditions as outlined in the following table:

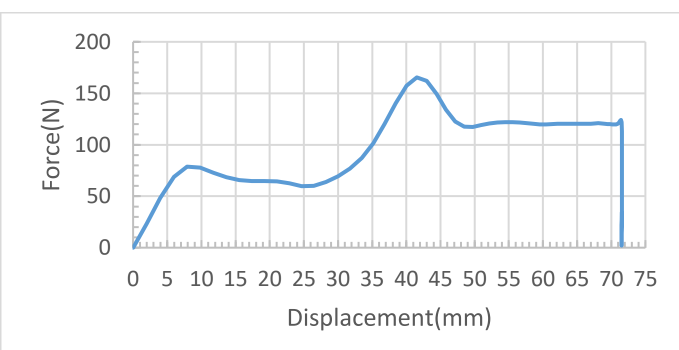
	-2°C				**-14°C**	
Test Number	**1**	**2**	**3**	**4**	**5**	**6**
Snow Weight(Kg)	8.3	7.2	7.5	10.05	6.2	6.5
Drop Height(cm)	20	10	15	20	10	15
Snow Fill Height(cm)	24	12	15	28	17	22
Indenter Depth(cm)	7	3	6.5	6	11	13

In the experiment, the indenter travelled to a depth of 7 cm, while the simulation predicted a depth of 7.2 cm, resulting in a minor error of 2.85%.

The following figures present the results: displacement vs time (Figure 1), Force vs time (Figure 2), and Force vs displacement (Figure 3). The first peak, representing the initial failure strength of the snow, was observed at an indentation depth of 0.9cm, whit a force of approximately 78N. Following this, the indenter entered, the plastic region, where stress increased as the indenter advanced through the snow, forming a densified zone beneath it known as a "pressure bulb." As the indenter transitioned into this zone, the pressure bulb reached its maximum size, leading to a plateau region where the force remained relatively constant, even as the indenter continued to move through the snow. Eventually, the force dropped to zero when the indenter came to rest.

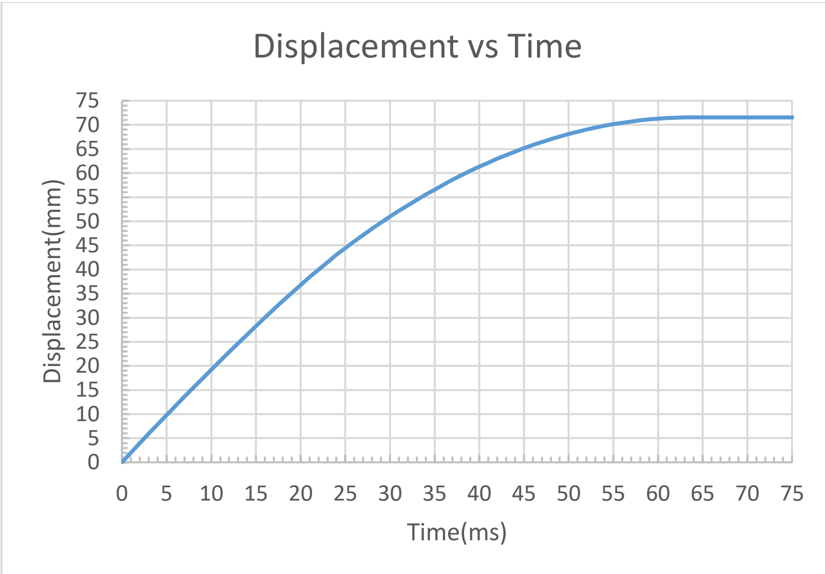
This study sheds light on the mechanical behavior of snow under impact, focusing on the snow's structural response during indentation.

Figure 1



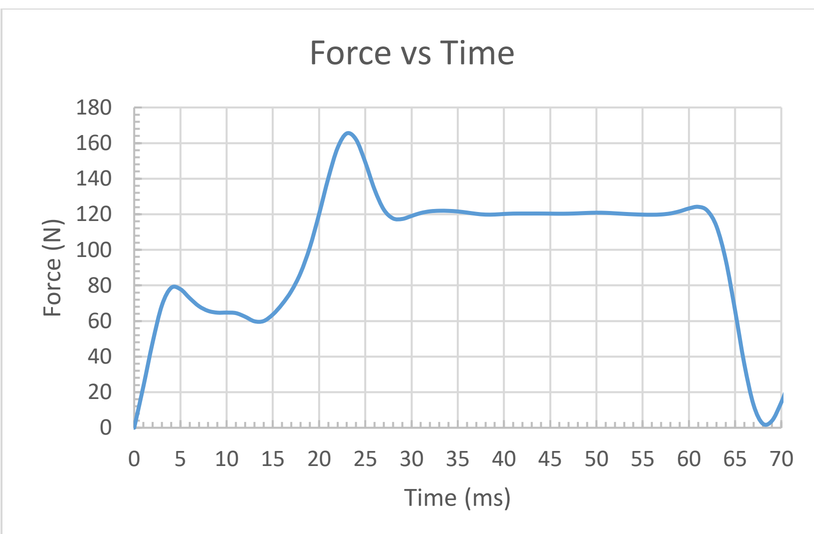
Figure(1) is the Force (N) vs Displacement (ms) graph. Zone I is the Densification zone and Zone II is the Plateau region

Figure 2



Figure(2) is the displacement (mm) vs time (ms) graph. The indenter comes to rest at 65ms after travelling a depth of 72 mm.

Figure 3



Figure(3) is the Force (N) vs time (ms) graph. The indenter observes a maximum resistive force of 165N

IV) Summary:

In summary, a snow model was developed using Smoothed Particle Hydrodynamics (SPH) elements, with material behavior represented by an elastic-brittle model based on the Mohr-Coulomb theory. The simulation results obtained using LS-DYNA closely match those from hardware tests. This modeling approach offers a reliable method for simulating snow behavior and can be applied to assess potential damages from natural events such as snow avalanches or vehicle collisions with snow heaps.

References:

1. Pascal Hagenmuller, Thiemo C. Theile and Martin Schneebeli (2014), Numerical simulation of microstructural damage and tensile strength of snow, doi:10.1002/2013GL058078.
2. Daisy Huang, Jonah H. Lee (2013), Mechanical Properties of snow using indentation tests: Size effects, doi: 10.3189/2013JoG12J064.
3. Ahmed M Abdelarzek, I Kimura & Y Shimizu (2014), Numerical Simulation of snow avalanches as a Bingham fluid flow using SPH method, DOI:10.1201/b17133-210.
4. Niklas Duchting (2018), Combined FEM-SPH simulations for ice in compression, DOI:10.15480/882.1658.
5. E.A. Podolskiy, G. Chambon, M. Naaim and J. Gaume (2017), A review of finite element modelling in snow mechanics, DOI:10.3189/2013JoG13J121.
6. Isabel Peinke, Pascal Hagenmuller, Edward Ando, G. Chambon, Frederic Flin and Jacques Roulle (2020), Experimental study of cone penetration in snow using X-Ray tomography, DOI:10.3389/feart.2020.00063.
7. Johan Gaume, G Chambon, Ingrid Reiweger, A. V. Herwijnen, Jurg Schweizer (2014), On the failure criterion of weak-snow layers using the discrete element method.
8. Markus von Moos, Perry Bartelt, Adrain Zweidler, Ernst Bleiker (2003), Triaxial tests on snow at low strain rate, DOI: https://doi.org/10.3189/172756503781830881.
9. Dan Koschier, Jan Bender, Barbara Solenthaler and Matthias Teschner (2019), Smoothed Particle Hydrodynamics Techniques for the physics based simulation of fluids and solids, DOI:10.2312/egt.20191035.
10. Jerome B Johnson, Mark A Hopkins (2005), identifying microstructural deformation mechanisms in snow using discrete-element modeling, DOI: https://doi.org/10.3189/172756505781829188.
11. Benjamin Reuter, Martin Proksch, Henning Lowe, A. V. Herwijnen , Jurg Schweizer (2019), Comparing measurements of snow mechanical properties relevant for slab avalanche release, doi: 10.1017/jog.2018.93.
12. Martin Mossner, Gerhard Innerhoffer , Kurt Schindelwig, Peter Kaps, Herwig Schretter, Werner Nachbauer (2013), Measurement of mechanical properties of snow for simulation of skiing, doi: 10.3189/2013JoG13J031
13. Ahmed M Abdelarzek, I Kimura & Y Shimizu (2016), Simulation of three-dimensional rapid free surface granular flow past different types of obstructions using the SPH Method, doi: 10.1017/jog.2016.22.
14. LS-DYNA Theory manual complied by John O. Hallquist; ISBN 0-9778540-0-0.
15. LS_DYNA Keyword User's Manual – I, II, III.