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SIMULATIONS OF DENSE SNOW AVALANCHES WITH GENERALIZED INTERPOLATION MATERIAL POINT METHOD: PRELIMINARY OUTCOMES

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Abstract. The paper presents material point method simulations of a dense snow avalanche replicating the avalanches observed at the Vallée de la Sionne test site. It has been observed that the dense snow avalanches behaviour is somewhere between the behaviour of very weak solid and very viscous liquid [1]. That is confirmed by difficulties in replicating such avalanches behaviour and the impact pressure with theories typical for fluid flows [2]. This paper results are based on numerical method used mainly for solids, though one allowing for extreme deformations [3-5]. The avalanche is modelled with a Mohr-Coulomb model, a simple constitutive model commonly used for modelling soils. The constitutive model has great many deficiencies and does not allow for modelling of all the complex behaviour of snow, however, the initial results presented are promising and show some agreement with the observed data. It is hoped that the presented approach can be refined and will lead to more accurate predictions of dense snow avalanches behaviour in the future.

1 INTRODUCTION

The snow avalanches may pose a threat to communities and infrastructure. Therefore, the prediction of avalanches outreach as well as impact pressures when an obstacle is hit are important problems. To investigate these issues, number of field tests sites monitor speed of avalanches and forces created by them upon hitting an artificial obstacle. These measurements are used, among others, to validate small-scale laboratory tests. However, such in-situ measurements are difficult and may be flawed for several reasons.

A wide range of flow regimes have been observed in avalanches. These span from dry powder-like avalanches, which generally move quicker to wet snow avalanches which have low velocity. The pressure recorded for quick avalanches include large number of impulses and significant variability. Such avalanches can also be modelled with methods belonging to fluid dynamics with significant success.

However, it is particularly difficult to model wet snow avalanches as they behave in the regime transitory between solid and fluid. The paper aim is to model an abstracted wet snow avalanche hitting an instrumented pylon with Generalized Interpolation Material Point Method (GIMP), introduced by Bardenhagen & Kober [4].

Figure 1. Instrumented pylon on a slope in the Vallée de la Sionne, Swiss Alps. Photos courtesy of Dr Emmanuel Thibert (National Research Institute of Science and Technology for Environment and Agriculture IRSTEA) and Dr Betty Sovilla (WSL Institute for Snow and Avalanche Research SLF).

2 TEST SITE IN THE VALLÉE DE LA SIONNE, SWITZERLAND AND THE AVALANCHE DATA

The test site in the Vallée de la Sionne, Swiss Alps (for detailed description see [6]) monitors occuring real-scale avalanches. The avalanches, both of natural origin and man-induced hit a heavily instrumented pylon (see Fig. 1). The pylon, 20m high, 60 cm wide and 1.5 m long measures avalanche pressures with high-frequency piezo load cells located at 0.5m, 1.5m, 2.5m, 3.5m, 4.5 and 5.5m above the ground. The optical sensors located on the sides of the pylon measure avalanche speed. There are also flow depth sensors on the pylon.

The observed avalanches falls into several categories. They can be, for example, dilute / dense (depending on snow density), or dry / wet (depending on the amount of moisture in snow). Further qualification of avalanches may be done with respect to their Froude number, see [2].

The piezo pressure sensors mounted on the pylon have either 10 or 25cm diameter. It appears that size of these sensors does not affect the average pressure measured; however, it seems that the peak magnitudes of stress decrease with sensor dimension [2].

This paper shows some initial outcomes of simulating of a wet-dense, relatively quick avalanche with Generalized Interpolation Material Point Method (GIMP).

3 GENERALIZED INTERPOLATION MATERIAL POINT METHOD (GIMP)

The Material Point Method has been developed by Sulsky et al. [3,7] as an evolution of the Particle in Cell method. This paper uses a Generalized Interpolation Material Point Method (GIMP [4]) which is an improved version of the classical Material Point Method.

The Material Point Method as well as GIMP falls into the category of meshless methods, even though it uses a background (usually static) grid, on which the equations are resolved in each step. GIMP is usually formulated as a fully explicit method (though implicit formulation is possible). In explicit formulation, simulation is resolved over time, which is divided into sufficiently small time-steps. The maximum time-step size is influenced by the grid size as well as particle velocity (Courant number).

In the Material Point Method the grid is cast over the simulation domain. Subsequently, all the materials within the simulation domain are discretised into particles (material points). The material points carry all the material information, as well as have position, mass and velocity. GIMP improves the classical Material Point Method as it additionally assumes that the material is smeared over finite particle domain which increases accuracy and reduces numerical issues in solution.

During calculations, in the beginning of every time step the mass and the momentum of the material points are transferred to the grid nodes using grid shape function and particle characteristic function. GIMP introduces these functions in more general way than the Material Point Method and creates particle domains instead of just having the material concentrated in points in space, as it is the case in the older formulation.

Subsequently, the nodal internal forces are computed (for which we also get the stresses from particles), as well as accelerations. These are transferred back and used for updating particles positions and velocities. From velocity gradients the deformation gradients and finite strains are computed. These are used for updating stresses and particle volumes. Afterwards, next time-step may be resolved. The more complete description of the GIMP can be found in [4] whereas validation of the method for some engineering problems is in [9].

4 NUMERICAL MODEL FOR THE AVALANCHE

Numerical simulation of natural avalanches is difficult. That is because of a great number of uncertainties which are present in natural avalanches, as well as due to numerical difficulties due to discontinuities and very large displacements. Few numerical methods can be applied for even qualitative modelling of an avalanche hitting an obstacle. This paper uses GIMP, as coded in open source Uintah 1.6.0 software (http://www.uintah.utah.edu/ [8]). The Uintah software has been enhanced with a Mohr-Coulomb model (for more details see [9-11]).

Table 1: Mohr-Coulomb parameters for snow

cohesion [kPa]	friction angle [deg]	dilation angle [deg]	shear modulus [kPa]	bulk modulus [kPa]	density [kg/m^3]
0.5	25	0	1,800	1,300	400

Table 2: Parameters for the contact layers

Material	cohesion [kPa]	friction angle [deg]	dilation angle [deg]	shear modulus [kPa]	bulk modulus [kPa]	density [kg / m^3]	friction coefficient [-]
slope surface	0.5	25	0	1,800	1,300	400	0.3
pylon surface	-	-	-	75,000	160,000	2,650	0.2

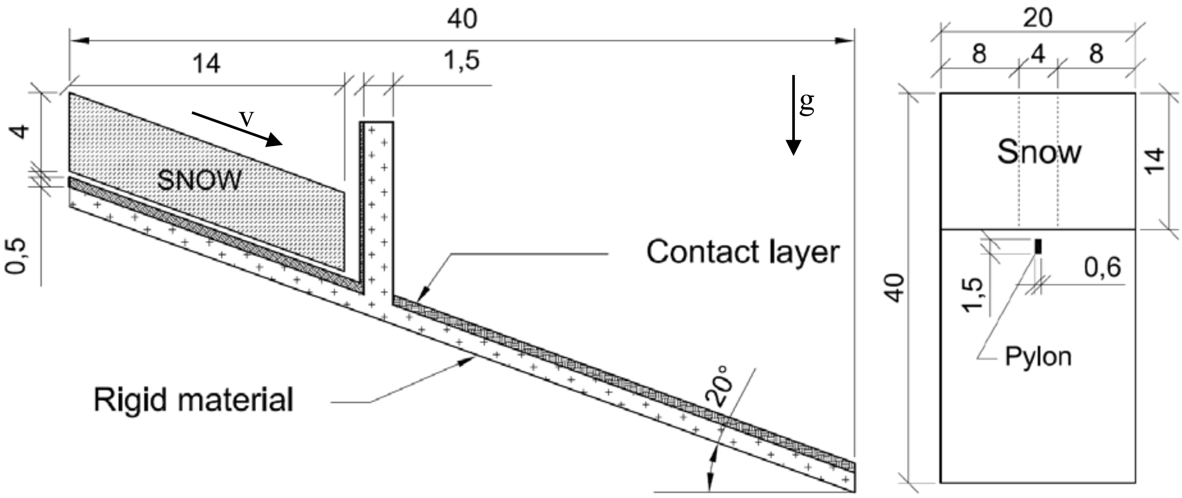

Figure 2. Schematic for the initial state of simulation: cross section through the pylon (left) and view from the top (right). All dimensions in meters.

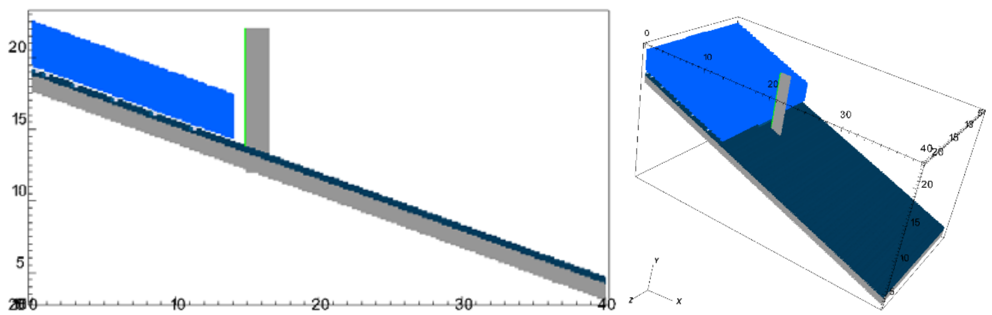

Figure 3. Side and 3D view of the initial state of the simulation. Different materials are shown with different colours.

4.1 Initial state

The scheme giving the initial state of the simulation is shown in Figure 2 and the initial actual simulation is given in Figure 3. The total size of the problem modelled is 40 m x 20 m. The slope angle is 20 degrees.

Only the 15m long, 20m wide part of avalanche is modelled. The thickness was taken as constant and equal to either 3 or 4m. The snow in the avalanche, as well as on the ground, is modelled as a Mohr-Coulomb material (see Table 1 for the model parameters, which were taken in line with suggestions in [1] and [12] and may be representative for the wet snow).

To reduce the computation time, the snow has been modelled with 2 different densities of material points. The two 8 m wide sides of the avalanche are approximated with just a single material point per grid cell, whereas the central 4m of snow is modelled with 2x2x2=8 particles per grid cell (which is also the density of material points in grid cell used for all other materials). The simulation begins with avalanche moving with the velocity of 10 m/s.

4.2 Contact

One of the most challenging parts of the calculations was to simulate the contact between the materials. In the model, the snow is interacting only with the contact layers on the rigid surface and on the pylon. These contact layers are attached to a rigid skeleton supporting it. The contact between snow block and contact surfaces is a frictional contact (as coded in Uintah, [13]). However, snow does not interact with rigid material at all. The material parameters for the contact layers are given in Table 2.

The contact layer simulating the slope surface is 0.5 m thick. That layer has been modelled with 2x2x2=8 particles per grid cell. The friction coefficient between the snow and that surface is taken as 0.3. However, in GIMP, the interaction between particles starts when the particle domains share common node. As such, to ensure smoother contact, the block of snow is moved away from the contact surface by 0.3 m.

The friction coefficient between the pylon contact layer and snow is set to 0.2. The pylon contact layer is single particle thick (thus mesh dependent) and positioned such that the grid boundary overlap with the boundary between the pylon and the contact layer. That ensures that the particles in the contact layer can move (and thus have some readable stress). That is essential, as the readouts from these particles on the pylon is taken as approximation of the contact pressure. Such approximation has been necessary as no direct way of getting contact forces exist in the standard Uintah 1.6.0 software.

4.3 Grid densities

It is well known that in problems which involves material separation (that is losing contact between the material points), the simulation results may significantly depend on the grid density. Most often, material separation is unwelcome, as it breaks the assumed continuous material and should be avoided. However, in the simulation of the avalanche, the impact on the pylon forces the separation of the particles. Therefore, the impact of the grid density on the simulation results had been carefully investigated. The simulations have been performed with a wide range of grid densities. They range from 2 grid cells per meter in each direction (2x2x2) to 4x5x5 cells per meter (4 cells per meter in the x direction). The problem dimensions have been kept (almost) constant during all the simulations. The number of particles in each grid cell was unchanged in all the simulation and is independent from the grid density.

5 SIMULATION RESULTS

Number of simulations have been done using different grid densities and two initial depths of the avalanche (3 & 4 meters). The results have been assessed qualitatively, that is whether the typical features of avalanche hitting an object are recovered. Additionally, the approximate values of contact stresses on the pylon were obtained and compared to the recorded results from the pylon sensors.

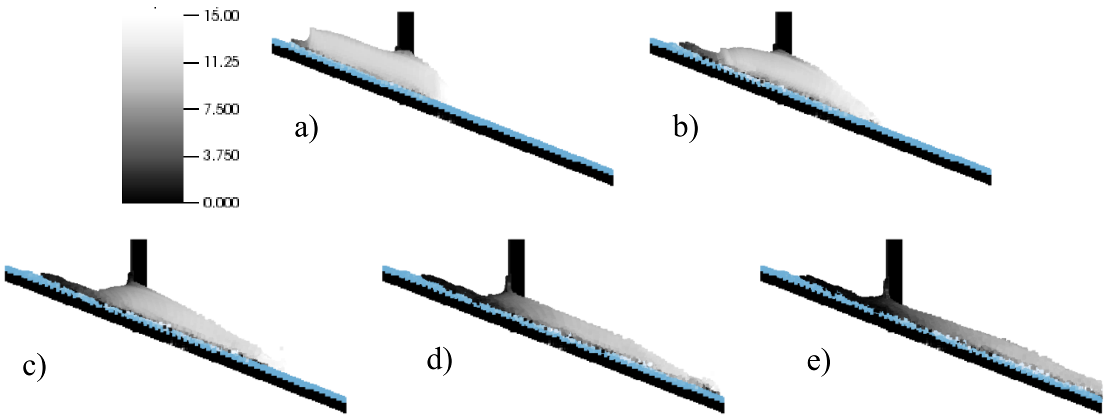

Figure 4. Velocity of the avalanche at simulation time 0.5, 1.0, 1.5, 2.0 and 2.5s. Side view. Grid density 3x4x4 (horizontal x height x depth) cells per meter.

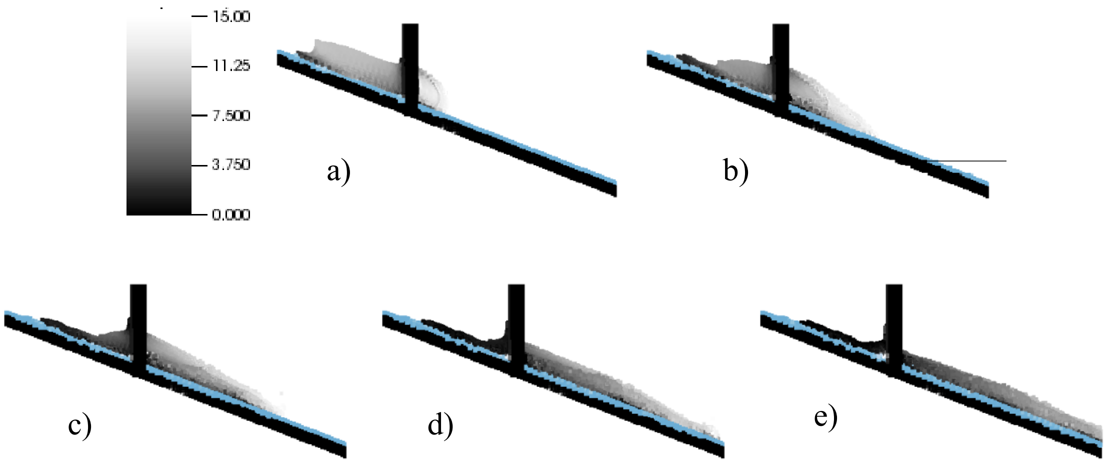

Figure 5. Velocity of the avalanche at simulation time 0.5, 1.0, 1.5, 2.0 and 2.5s. Intersection through the pylon. Grid density 3x4x4 (horizontal x height x depth) cells per meter.

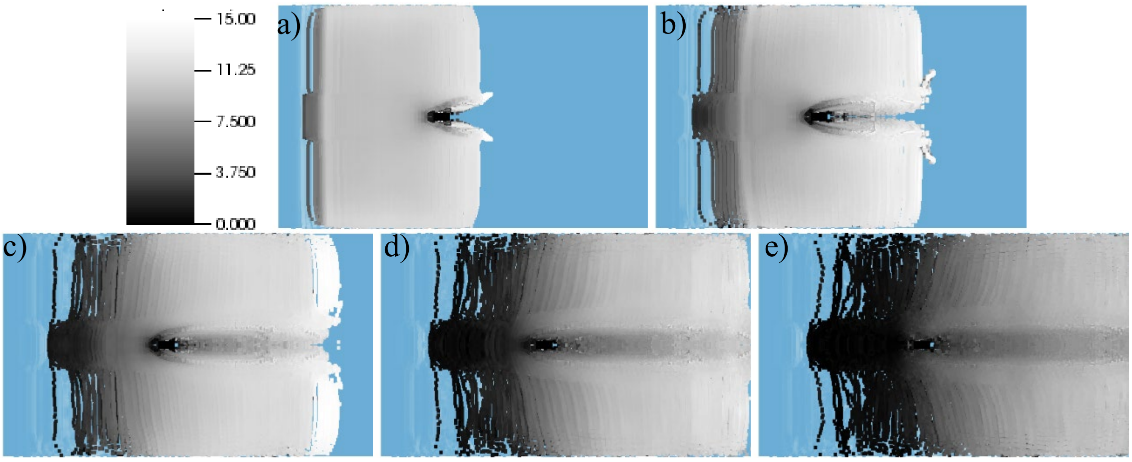

Figure 6. Velocity of the avalanche at simulation time 0.5, 1.0, 1.5, 2.0 and 2.5s. View from the top. Note some particles are stuck on the ground after the simulation (black lines). Grid density 3x4x4 (horizontal x height x depth) cells per meter.

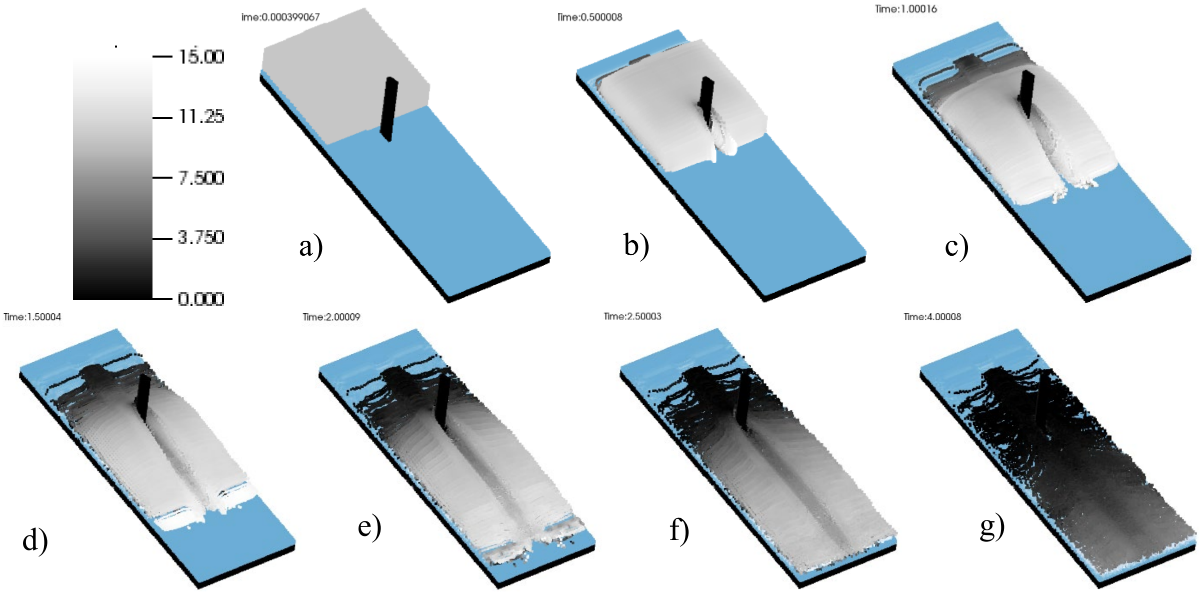

Figure 7. Velocity of the avalanche at simulation time 0.5, 1.0, 1.5, 2.0, 2.5 and 4.0s. Note some particles are stuck on the ground after the simulation (black lines). Grid density 3x4x4 (length x height x depth) cells per meter.

5.1 Qualitative agreement of the results

Before seeking good quantitative agreement between simulation and observed avalanche behavior, it is important to investigate whether the simulated avalanche exhibit number of behavior observed in real avalanches. The GIMP simulations perform rather well here. The wedge (dead zone) is created in front of the pylon, see Figures 5 and 6 a)-c) (all the data visualized with VisIt [14]). Also, some snow stays behind the pylon, Figure. 5 d), e) (note that this situation does not last till the end of simulation which is due to limitations of constitutive model used). The velocity profiles around the pylon look realistic, see Figure 5 b) – d). Finally, the avalanche initially divided by the pylon is becoming unity after covering some ground as evidenced in Figures 6 c)-e) and 7 c)-g).

5.2 Quantitative agreement of the results

It is interesting to see how the available contact pressures compare to these obtained in the simulation. Unfortunately, such a direct comparison has not been possible at this stage. Currently, only the values of x-direction components of stress at particles at similar height to the sensors, but not the contact pressures per se could be obtained from the calculated results. Presumably, at least initially, stresses in single layer of particles resting on rigid material should not be very different to the actual contact pressures. That has been partially confirmed by setting elastic parameters of Pylon contact material: the bulk modulus to 100 MPa and the shear modulus to 150 MPa which correspond to Poisson ratio of 0. For that case, the stresses were very similar to these obtained with elastic values given in Table 2. Therefore, the interaction between the particles in the contact zone is probably not a major source of error (at least for the stresses in particles close to the middle of the pylon). On the other hand, when the stress is reduced, the particle will bounce back due to elastic forces. In such case particle inertia will significantly affect the stresses. As such, only the readout of stresses in the initial time (before the stress is reduced) could be close to the actual contact forces. However, the particles stress will be affected by the grid cell size anyway, as the stresses are resolved over whole grid cell, as well as the particle domain size.

In the simulation the axis of symmetry of the pylon corresponds to the grid boundary. That smooths the snow flow around the pylon and reduce the stresses. However, it also means that the particles from which the stress is read are moved somewhat to the side and do not correspond to the actual sensor position.

The avalanche modelled, with the code number of 6236 had wet-dense core with a powder layer [2]. That spatial non-uniformity has not been modelled – the material parameters of the snow may reflect a uniform wet-dense avalanche instead. Also, the 6236 avalanche has been recorded for approximately 40s, whereas the avalanche modelled impacted the pylon approximately during 1.5 second period.

To characterize the avalanche 6236 more accurately (recouping data from [2]), it was recorded as having varied height, rising from a meter to approximately 4 m. The measured velocity ranged from below 5 m/s (initial part of the avalanche) to approximately 7-10 m/s when it reached its peak height, which was approximately 4 m. The stresses were significantly oscillating. At the peak time, with the avalanche having the highest speed, the contact pressures were between approximately 100 and 300 kPa at the 0.5 m sensor. Higher up, the stresses reduced to approximately100 kPa (oscillating approximately between 50 and 150 kPa) and at 3.5 m they were mainly between 50 and 100 kPa with peaks reaching above 100 kPa. At 4.5 m, which was almost certainly above the wet-dense avalanche, the readouts were above 25 kPa and below 50 kPa.

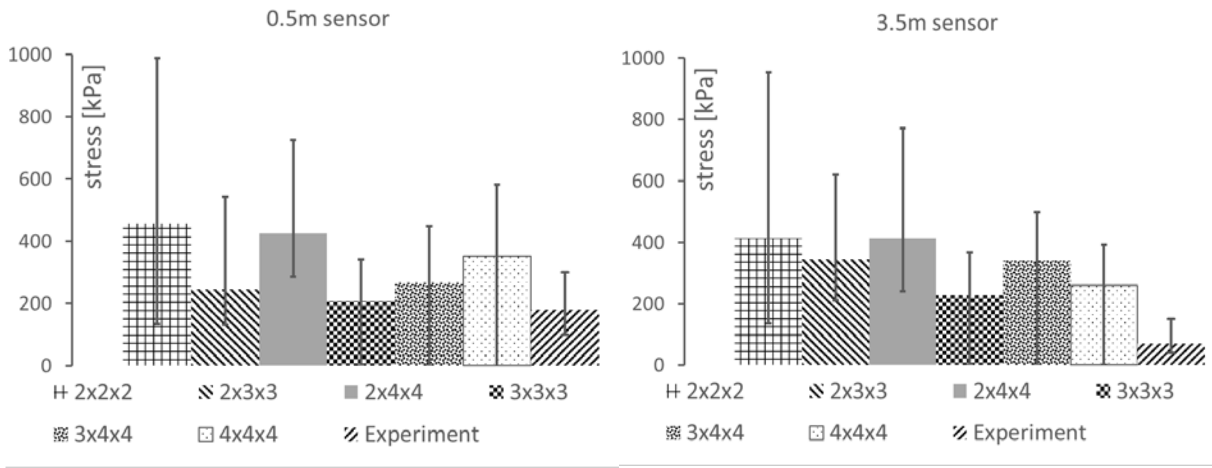

Figure 8. Grid density influence on the average stress on the pylon. The bar show averaged stress over the first 0.4 sec after the impact of the avalanche. The stresses shown are at points approximately at 0.5m and 3.5m. Error bar indicate maximum and minimum stress recorded. Grid cell densities varies between 2 cells per meter in each direction (2x2x2) to 4 cells per meter in each direction (4x4x4). Values for the pylon contact pressures (indicated as experiment) are based on [2] and approximate.

For this comparison, a simulation of initially 4m high avalanche were taken which resulted at acceptable heights of avalanche at the pylon. The results of simulations are given in Figure 8. It can be clearly seen that the modelled maximum and average stresses are too high. That may be partially due to generally too high speed of the avalanche at the pylon. In the simulation, the avalanche velocity was mainly between 10 and 15 m/s range, which is higher than the recorded values. Additionally, the assumption of the uniform snow density corresponding to the wet snow was incorrect. As the recorded velocity of the avalanche increases with the avalanche height, the lower recorded pressures are likely due to differences in the snow density.

The grid density does not appear to affect results too significantly. Of course, the results for the coarsest grid 2x2x2, in which the pylon is modelled by just 2 particles (and is hit by just two particles of avalanche) are crude, as indicated by the difference by the maximum and minimum value (Fig. 8). However, for the finer meshes (with cell size of the hitting plane being 1/3m and 1/4m, denoted by the last number being 3 or 4 respectively) the differences between the results appear to be more acceptable. Still, the differences in stresses in simulations are probably mainly due to numerical reasons, whereas in the natural avalanches, they are due to natural factors.

Nonetheless, as GIMP is used in the shown simulations beyond its intended use range as the avalanche separates upon hitting a pylon and rejoins later, the differences between grids seem to be acceptable. Nonetheless, more control over separation of the material would be desirable as some difficult to account for mesh dependency is theoretically unavoidable with GIMP.

6 CONCLUSIONS

The paper presented initial results of simulation of a snow avalanche hitting an obstacle. The simulation recovered well the behavior of real avalanche qualitatively. In particular, the qualitative behavior of avalanche and leftover snow at the pylon has been well recovered.

Additionally, the final joining of the avalanche after hitting the pylon is also observable – something that would be difficult to achieve with most continuous numerical methods. The avalanche speed profile around the pylon is also qualitatively agreeing with experimental data.

The paper also compared the stresses on the pylon with the experimental data. The agreement should be improved further. The differences in the results may be due to number of issues. First, it appears that the speed of simulated avalanche should be decreased. Additionally, we do not know what material parameters are correct for given avalanche. The simulations shown are initial and not adjusted in order to improve the fit of the results. Finally, the avalanche has been modelled as uniform, whereas the avalanche we compared the results to is indicated as most likely non-uniform.

There are number of numerical shortcomings in the simulation. In particular, contact law and retrieval of contact pressures could be tweaked. Furthermore, Mohr-Coulomb is a very simple material model which is not very well validated for snow. As such, perhaps using a constitutive model uniquely suited for snow may improve the results. Finally, using a version of material point method enhanced such that for accurate modelling of separation and joining of particles would be possible (instead of relying on the hard coded mechanics of GIMP) would be welcome.

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