E3S Web of Conferences **415**, 01017 (2023) https://doi.org/10.1051/e3sconf/202341501017
DFHM8

Multi-component avalanches for rock- and ice-falls to potential debris flow transition modelling

Jessica Munch[1*], *Perry* Bartelt[1], and *Marc* Christen[1]

[1]WSL Institute for snow and avalanche research SLF, Flüelastrasse 11, 7270 Davos-Dorf, Switzerland

Abstract. Rock/ice avalanches are complex gravitational flows involving three important physicalprocesses: entrainment, phase-changes, and flow transitions. The basic complexity of modelling rock/ice avalanches lies in the fact that the flow is a mixture of rock, ice, water, snow, soil sediments. The interaction of these components can lead to flow transitions which is difficult to model with simplified flow rheologies. For example, a flow initially composed of rocks and ice can transition into a long-runout debris flow, dependent on the entrainment of water, water-saturated sediments and/or snow. The dynamic behaviour of rock/ice avalanches is therefore highly difficult to predict because the flow mixture is dependent on the hydrological and geomorphological properties along the avalanche track. These properties can vary from year to year but even from season to season. The problem is intensified by the fact that frictional shearing can produce enough heat energy to melt ice and snow, leading to additional water in the flow. In this contribution, we present a new RAMMS module specifically designed to simulate single- and multicomponent avalanches of rock, ice, water, snow, and ice. The rheology of the flow is treated by using the concept of component activation energy. The model includes both snow and sediment/water/ice entrainment modules. A unique feature of the model is that it tracks the temperature of the rock, ice and water phases and therefore can treat phase changes. We apply the model on the Chamoli case-study to highlight the potential and present limitations of the model..

1 Introduction

Multi-component rock/ice avalanches occur at a lower frequency than snow avalanches or debris flows, but usually lead to larger consequences in terms of infrastructure destruction and human loss of life. Some events that occurred over the last years include the Piz Cengalo, 3368 m a.s.l, rock and ice avalanche that occurred in August 2017. It initiated with the release of 3.106 m3 of rock which fell on to an ice-glacier, leading to the entrainment of 0.6 million cubic meters of ice [1, 2]. The flow then transitioned into a debris flow that reached the village of Bondo in the Grisons, Switzerland, causing casualties and infrastructure destruction [2] . Another major example of this kind of event it the rock and ice avalanche that took place in Chamoli area, in India, in February 2021. In this case, 27.106 m3 of material fell from Ronti Peak, 5600 m.s.l,travelled through the Rishiganga and then Dhauliganga valleys, leading to the destruction of two hydroelectrical projects and 204 casualties [3-5] .

These events have been widely studied from a field perspective, but also using seismic data, numerical models etc. However, most the of the numerical models used so far focused on one-phase flow [5-7]. To accurately model multi-component avalanches, we hold that it is necessary to consider all the avalanche components in the form of separate phases, such as snow/ice, rocks, and water. Indeed, it has been suggested [8, 9] , that the water content of gravitational flow strongly influences the rheological properties of the flow and therefore the final runout distance and hazard potential. The water can arise from many different sources. Indeed, water is not necessarily present in the flow at the beginning, however, when the ice melts, or when ground water/river/glacier water is entrained, the water content can increase dramatically. Hence, the different materials present in the avalanche should be allowed to interact, and phase changes should be considered when attempting to model such phenomena. Moreover, the importance of entrainment in numerical models is common to various gravitational flows [10, 11], and we think that it is crucial to multicomponent avalanches as, depending on the flow composition, which is likely to be strongly affected by entrained material, the runout distances and potential to debris flow transition will vary.

In this work, we are introducing a new module of the RAMMS software [12] specifically built to model avalanches that contain rocks, ice, snow and water. We will first shortly describe the governing equations before applying the model to the Chamoli event from 2021 and assess which are the controlling parameters for the water content in the flow.

2 Methods

* Corresponding author: jessica.munch@slf.ch

The module is built on the depth-averaged conservation of mass and momentum for all the phases involved in the flow:

$$\partial_t \widehat{H}_\Phi + \nabla \cdot (H_\Phi \boldsymbol{V_\Phi}) = \dot{M}_{\Sigma\to\Phi} - \dot{M}_{\Sigma\to\Pi} \quad (1)$$

With

$$\widehat{H}_\Phi = \frac{\rho_i}{\widehat{\rho_\Phi}}\left(h_i + \frac{\rho_s}{\rho_i} h_s\right) + \frac{\rho_r}{\widehat{\rho_\Phi}} h_r + \frac{\rho_w}{\widehat{\rho_\Phi}} h_w \quad (2)$$

Where $\widehat{H}_\Phi$ is the height of the flow, h is the height of each material in the flow, and ρ is the density for each material, the subscript r stands for rock, i for ice, w for water, and s for snow. $\widehat{\rho_\Phi}$ is the density of the co-volume of the flow [13]. The velocity of the avalanche core is given by $\boldsymbol{V_\Phi}$. $\dot{M}_{\Sigma\to\Phi}$ represents the mass entrainment rate by the core and $\dot{M}_{\Sigma\to\Pi}$ is the mass loss rate from the core to the powder cloud.

The momentum conservation in the slope parallel direction is written as:

$$\partial_t(\widehat{H}_\Phi \boldsymbol{V_\Phi}) + \nabla \cdot \left(\widehat{H}_\Phi \boldsymbol{V_\Phi} \otimes \boldsymbol{V_\Phi} + \frac{g\widehat{H_\Phi^2}}{2} I\right) = \boldsymbol{G} - \frac{V_\Phi}{||V_\Phi||}[\boldsymbol{S}_\Phi + ((1+r)\dot{M}_{\Sigma\to\Gamma} + \dot{M}_{\Sigma\to\Pi}||\boldsymbol{V_\Phi}||)] \quad (3)$$

with G the gravitational constant, g its vertical component, I the identity matrix, $\boldsymbol{S_\Phi}$ the shearing forces acting on the core, r is the splashing restitution coefficient, $\dot{M}_{\Sigma\to\Gamma}$ the mass splashing rate, $\dot{M}_{\Sigma\to\Pi}$ the mass of entrained material that is transferred to the powder cloud. The complete set of differential equations is given [13].

An important aspect of the code is the heat transfer between the different phases that potentially leads to the melting of the ice contained in the flow. Heating comes from two different sources: shear heating of the materials and sensible heat transfer between the rock, ice/snow, and water components.

The temperature of the flow T_Φ is related to the internal heat energy E_Φ via the specific heat capacity c_Φ of the materials by:

$$E_\Phi = \hat{\rho}_\Phi c_\Phi T_\Phi \widehat{H}_\Phi \quad (4)$$

This leads to the following energy equation:

$$\partial_t \mathrm{e_n} + \nabla \cdot (e_\mathrm{n} \boldsymbol{V_\Phi}) = \dot{f}_\mathrm{n} \quad (5)$$

Again, Eq. 5 contains n=3 equations, e_n being the internal energy for each phase: n=rock, water, and ice and snow that are treated together. $\dot{f}_n$ is the source term for each material.

The entrainment is computed as in ([11]), different areas with different compositions in terms of rock, ice, snow, water and subsequent rheologies and maximum erosion depth are defined.

3 Chamoli event, February 2021

On February 7th, 2021, 27.10^6 m^3 of rock (80%) and ice (20%) ([5]) fell from Ronti Peak, 5600 m a.s.l, in Chamoli, Uttharakhand district, India. The flow went down in the Rishiganga and then Dhauliganga valleys, potentially remobilizing material from an avalanche that occurred in 2016 ([5]), as well as sediments in the valley and water from incoming rivers. Several sources of water can be identified to explain the transition from the initial purely rock and ice flow to the debris flow that damaged infrastructures and caused human fatalities. The sources likely to be 1) water produced from the melting of the ice initially present in the flow, 2) water entrainment from the ground or coming from a secondary release, 3) water produced from ice entrained and melting.

In this work, we run simulations for the Chamoli area, using the proportions of rock and ice suggested for the event, and vary the heat transfer coefficients, the presence or absence of a secondary release zone that could be triggered by the avalanche when it crosses unconsolidated deposits from previous multi-components avalanches, and composition of the entrained material. We want to assess how these different elements influence the amount of water present in the flow and the potential for a transition to debris flow.

We performed 7 sets of simulations that are detailed in Table 1. We used a resolution of 20 m and ran them for 1500s. We defined a main release zone at Ronti Peak, 66 m deep, of about 25.10^6 m^3, made of 80% rocks and 20% ice, with a density of 2500 kg/m^3. In some simulations, we defined a secondary release zone in the deposits area of the 2016 avalanche, we set it made of 70% rocks and 30% ice, its volume is about 3.7 millions of cubic meters, and we set it to release 80 s after the initial release, at the same time as the flow reaches the concerned area. All the releases are done at a temperature of 0°C. We ran the simulations with various heat coefficients and with and without ground material entrainment. The entrainment layer has been defined uniformly over the computation domain, with a depth of maximum 10 m at 5200 m high and a loss of snow layer thickness of 0.03 m per 100m elevation loss, and at a temperature of 0 °C.

4 Results

To start with general observations, we note that simulations which do not involve material entrainment stop before the maximum time allowed for the simulation, due to a lack of momentum. The flow comes down at up to 90 m/s and goes through the Rishiganga valley. By the time it reaches the point A (30.466524, 79.733131, red arrow Fig. 1) its velocity decreases to 50 m/s and keeps on decreasing until stopping when no entrainment. Water starts being produced as soon as the falling material reaches the valley floor. A large amount of water is then produced around the point A (Fig. 1). Over time, the water content in the flow increases, especially when material is entrained, and it concentrates at the front of the flow (Fig. 1.).

When looking at the water content evolution in the flow with time for the different scenarios, the highest amount of water is produced in the simulation involving a high heat transfer between rocks and ice, a secondary release as well as material entrainment, then come the simulation with a high heat transfer between rocks and ice, entrainment but no secondary release, then the one with a low heat transfer between rocks and ice, no secondary release and material entrainment.

Table 1: Simulation settings. In the release compositions, R stands for rock, I for ice, S for snow, W for water, the composition is given in percentages of the different materials.

Simu-lation	Heat transfer rock-ice	Heat transfer rock-water	Heat transfer water-ice	Secondary release composition (in %)	Material entrainment and composition (in %)
1	10^3	10^3	10^3	x	x
2	10^6	10^3	10^3	x	x
3	10^6	10^6	10^6	x	x
4	10^3	10^3	10^3	x	R60I30W10
5	10^6	10^3	10^3	x	R60I30W10
6	10^6	10^3	10^3	R 70 I 30	X
7	10^6	10^3	10^3	R 70 I 30	R60I30W10

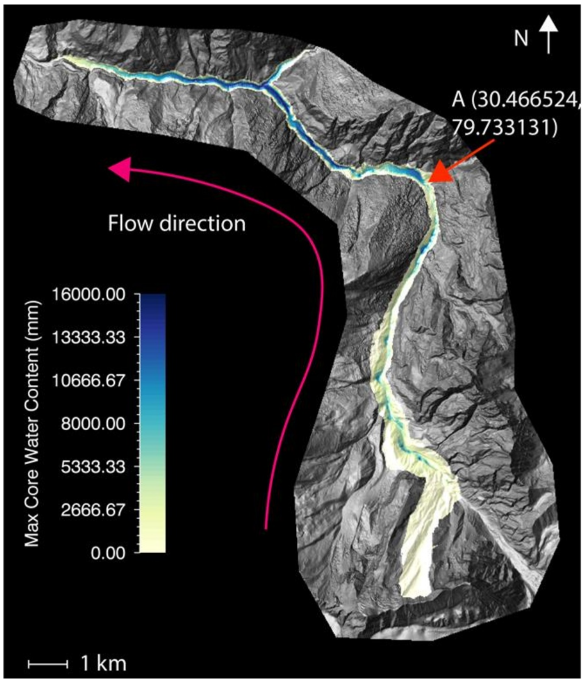

Fig. 1: Maximum water content in the flow (in mm) at 1500s after avalanche start for simulation 1. Water height in the core is up to 16 m in some locations towards the front of the flow.

All those simulations were stopped because of the maximum time allowed for the simulation to run. The simulations without entrainment stopped before, due to a lack of momentum, the highest water quantities being found in the scenario with a secondary release and a high heat transfer between rocks and ice, then quite close together the ones with no secondary release and 1) a high heat transfer between all of the materials and 2) a high heat transfer between rocks and ice, which suggests that the main cause for melting the ice comes from the heat transfer between rocks and ice. The simulation with a low heat transfer between all the materials was the first one to stop but also the one producing the least amount of water. We also observe an increase of the water amount in the flow at 80s, up to 1.10^6 m^3 right after the secondary release (Fig. 2.).

5 Discussion

The water starts being produced when the avalanche core reaches the valley floor, which suggests that the shear heating produced is enough to start melting the ice at that point. The important water production around the point A can also be explained by shear heating which is likely on increase due to lateral curvature of the valley.

Heat transfer within the flow, entrainment and secondary release are all responsible for water production as the flow propagates. Heat transfer appears to be the predominant process at the very beginning of the avalanche, until the secondary release occurs. Material entrainment is largely contributing to water input in the flow, especially on the long run, but this observation must be considered with caution as it is likely to strongly depend on the composition of the entrainment layer.

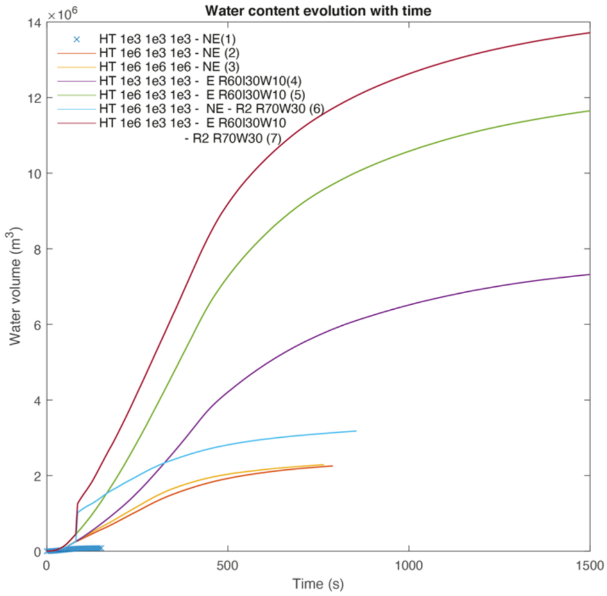

Fig. 2 : Evolution of the water content in the flow with time. Simulation numbers are given in the legend.

The water content we observe in our simulations are lower, within the range and higher than the ones given by ([3, 5]), depending on the presence of a secondary release, and on material entrainment. The melting cannot explain alone the final amount of water in the flow; however, depending on the composition of the entrainment layer and/or of the secondary release, the amount of water computed can dramatically change (Fig. 2). This emphasizes the importance of constraints regarding the composition and thickness of the entrainment layer, as well as of potential secondary releases. Progress could be made in this domain via field data and remote sensing, as well as observations of past events.

Concerning the evolution of melt water production via heat transfer, we note that water production rate decreases when the flow travels between the Rishiganga and Dhauliganga rivers, in simulations without entrainment. There, we observe a general decrease of the flow velocity, which would imply a lower shear heating possibly leading to a general decrease in heat transfer. Shear heating and heat transfer between the phases must be further investigated, especially regarding the values for the heat coefficients, as it seems to strongly influence water production within the flow and remains poorly constrained by experimental data.

The observation about the flow travelling further in the simulations involving a secondary release and entrainment fits the findings of [8, 9] regarding the lubricating effect of water in the flow but that increase might also be related to the fact that there is more material in the flow in general.

Finally, our simulations show that the water mostly accumulates at the front of the flow. In our model, the water is bonded to the flow, there is no phase separation possible for now, which means that we cannot have a transition to a debris flow. We can only suggest that this accumulation of water could be responsible for that transition. The result as such could be then used as an initial condition for a debris flow model to then simulation the runout of the debris flow resulting from the multi-components avalanche.

6 Conclusions

We are developing a new module for the RAMMS software that is designed to model multi-component avalanches. The program allows for the definition of different phases which interact with each other, leading to heat transfer and phase changes. It allows for the quantification of water production within the flow due to ice melting, ground material entrainment and secondary releases in areas that could be massively remobilised by the passing avalanche. The module allows for tracking the thermo-mechanical evolution of the different phases involved in the flow. Preliminary results show that the water content of the flow increases with time due to all the factors mentioned previously, the main ones being secondary releases and material entrainment. Depending on the composition of the secondary release and entrainment layer, the final amounts of water in the flow vary substantially, which highlights the importance of data as accurate as possible on the areas that could potentially be on the track of rock-ice/multiphase avalanches. Further work is necessary to calibrate the heat transfer coefficients responsible for sensible heat transfer between the phases, to assess the amount of water that can be produced by melting the ice present in the flow.

References

1. F. Walter, F. Amann, A. Kos, R. Kenner, M. Phillips, A. de Preux, M. Huss, C. Tognacca, J. Clinton, T. Diehl, Geomorphology **351** (2020)
2. W.-I.f.S.-u. L. SLF, WSL, WSL Gutachten G2017.20: Modellierung des Cengalo Bergsturzes mit verschiedenen Tahmenbedingungen, Bondo, GR. (2017)
3. P. Rautela, , S. Khanduri1 S. Kundalia, GC Joshi, R. Jugran, Journal of Environmental & Earth Sciences **3** (2021)
4. G. o I.Disaster Management Division (National Emergency Response Centre). Ministry of Home Affairs. Situation report on the glacial outburst at Reni in Chamoli District Uttarakhand (2021)
5. D.H. Shugar, M. Jacquemart, D. Shean, S. Bhushan, K. Upadhyay, A. Sattar, W. Schwanghart, S. McBride, M. Van Wyk de Vries, M. Mergili. Science **373**, 6552 (2021)
6. T. Zhang, Y. Yin, B. Li, X. Liu, M. Wang, Y. Gao, J. Wan, K.R. Gnyawali, Journal of Rock Mechanics and Geotechnical Engineering **15**, 2 (2022)
7. M. Mergili, M. Jaboyedoff, J. Pullarello, S. P Pudasaini, Natural Hazards and Earth System Sciences **20** (2020)
8. Q. Yang, Z. Su, Z. Li, H. Liu. *Influence of ice content on the run-out of rock-ice avalanches.* in Workshop on World Landslide Forum, 587-91. Springer (2017)
9. R. Sosio, G.B. Crosta, J.H. Chen, O. Hungr, Quaternary Science Reviews **47** (2012)
10. C. Kang, D. Chan, F. Su, P. Cui, Landslides **14** (2017)
11. F. Frank, B. W McArdell, C. Huggel, A. Vieli, Natural Hazards and Earth System Sciences **15** (2015)
12. M. Christen, J. Kowalski, P. Bartelt, Cold Regions Science and Technology **63** (2010)
13. P. Bartelt, M: Christen, Y. Bühler, O. Buser, Numerical Methods in Geotechnical Engineering **9** (2018)