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Interactive comment on “Role of friction terms in two-dimensional modelling of dense snow avalanches” *by* Marcos Sanz-Ramos et al.

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Author’s response to referee Christophe Ancey comments

COMMENT:

The paper shows how the Iber numerical code (used in hydraulics) has been extended to cope with snow avalanches. It also presents three applications and discusses the part played by the various contributions to friction.

Major comments:

This paper’s strength lies in the extension of Iber to model snow avalanches. Iber is a freely available software based on efficient finite-volume techniques for solving the

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Saint-Venant equations, preprocessing and post-processing tools, and a user-friendly interface. Apart from commercial software such as RAMMS, existing tools are academic tools with no user interface, so Iber as a newcomer is welcome.

ANSWER:

The authors want to firstly thank Mr. Ancey the time and dedication for reviewing the manuscript, besides his interest for Iber and its extension for simulation of dense-snow avalanches. Answers to each general comment are detailed below:

COMMENT:

The paper is also interesting for two reasons: Developing numerical avalanche-dynamics models is a longstanding problem. To the best of my knowledge, most existing models are based on finite-volume techniques, following the idea proposed by Jean-Paul Vila in the 1980s (Vila, J.-P., Modélisation mathématique et simulation d'écoulements à surface libre. La Houille Blanche, 6/7, 485-489, 1984; Vila, J.P., Simplified Godunov schemes for 2*2 systems of conservated laws, SIAM Journal of Numerical Analysis, 23, 1173- 1192, 1986. Vila, J.P., Sur la théorie et l'approximation numérique des problèmes hyperboliques non-linéaires, application aux équations de Saint-Venant et à la modélisation des avalanches denses, Ph.D. thesis thesis, Paris VI, 1986.). In the early 2000s, a benchmark comparison of numerical models showed how the numerical outcome was sensitive to the algorithm details (Barbolini, M., U. Gruber, C.J. Keylock, M. Naaim, and F. Savi, Application of statistical and hydraulic-continuum dense-snow avalanche models to five European sites, Cold Regions Science and Technology, 31, 133-149, 2000.). Today, 20 years later, if I compare my code based on clawpack (available from github) and Shaltop (developed by François Bouchut and Anne Mangeney), I got significant differences in the avalanche deposition zone in many cases. Developing new models and making them available should help us to improve the state of art, and see why (or when) some numerical approaches to the Saint-Venant equations are more efficient.

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ANSWER:

The authors are in agreement with this general comment, and thank the provided bibliography. The aim of this paper is not to compare different numerical models or schemes, but the effects of the friction terms on the results when using one model. As the referee has already explained, there will be differences between the solutions. Herein two laboratory experiments are analysed, but only for Case 1 (Hutter, Exp. 117) the numerical experiments of Bartelt are shown, in order to emphasize the discrepancies regarding the role of the friction terms, through a brief comparison at the end of the section between the results obtained by the different models.

Before the advent of commercial software (like Aval1d and Ramms), avalanche engineering was mostly the field of trained and experienced practitioners. The increasing availability of numerical tools has allowed a wider community of users (including untrained practitioners and governmental agencies) to access computational avalanche-dynamics models. Paradoxically, this has led to a significant decrease in the quality of expertise offered. Many people have been fooled by the apparent high resolution of numerical outcomes, confusing numerical resolution and prediction accuracy. Giving access to different avalanche-dynamics codes should make people more aware of uncertainties affecting numerical simulations. As Bruno Salm stated in his last review paper, “The presented models are allâĂŤup to the present dayâĂŤsomehow uncertain. Therefore, only relative simple models with few parameters are significant. An increase of complexity of models does not necessarily mean an increase of accuracy or a better hazard mitigation strategy.” (Salm, B., A short and personal history of snow avalanche dynamics, Cold Regions Science and Technology, 39, 83-92, 2004.).

ANSWER:

The authors are also in agreement with this comment. Numerical tools are a simplification of the reality, and the provided results, which also depend on the expertise of the technicians or modellers, should be taken carefully. This paper aims to show how quite big changes in the friction terms allow to achieve very similar solutions. Section 3 shows that, which is an issue directly related to the friction terms expression, and not to the numerical code, as shown in Section 3.1. In particular this is shown with the Case study 2 (Section 3.3), in which different combinations of the friction parameters provide a good fit to the experimental results for the two experiments analysed (see Figure 8). The model used herein follows the same strategy for simulating dense-snow avalanches as other numerical codes: the use of Voellmy-fluid approximation for assessing the friction terms. There exist several codes based on the solution of the same equations, the 2D-SWEs. Thus, in all of them specific parameters and numerical strategies must be used, and is used, to avoid a water-like behaviour of the snow (see Sections 2.2 and 4.2). We are especially in agreement with Mr. Salm's comment, and the results presented herein show precisely the behaviour of a relative simple model with few parameters. From our point of view, there are two options for the numerical modelling of dense-snow avalanches: to use "simple" 2D-SWE based models; or to use much more complex Computational Fluid Dynamic (CDF) models. There is still a lack of expertise for the last ones, surely they are the future, but meanwhile it is worth exploring the capabilities and behaviour of the first. As we said before, we agree in the importance of expert criteria, and we added the following sentence in the Conclusions section: L536: . . . without field data. On the other hand, quality expert criterion is fundamental in the evaluation of the simulation outcomes.

COMMENT:

That said, I think that the paper suffers from many shortcomings: This paper's ultimate goal is unclear to me. The introduction does not frame any scientific issue. I understand that the authors want to study the effect of friction on the bulk dynamics, but I have hard time understanding what the problem is. Voellmy's model is an empirical one. It shows usefulness in many engineering applications, but there is no proof that snow behaves like a Voellmy frictional material (as shown in my 2004 JGR paper, Coulomb performs better in many cases). Although Adolf Voellmy did not present the issue like this, I presume that he was annoyed with Paul Mougin's model based on Coulomb friction (Mougin, P., Les avalanches en Savoie, 175-317 pp., Ministère de l'Agriculture, Direction Générale des Eaux et Forêts, Service des Grandes Forces Hydrauliques, Paris, 1922.) because an avalanche experiencing Coulomb friction cannot reach a steady state. The avalanche accelerates or decelerates. Hence, no possibility of providing analytical estimate of avalanche velocity. By adding a turbulent-like term, Voellmy got around this issue. To date, fitting the Voellmy coefficients or predicting avalanche behavior remains a difficult challenge. Adding new contributions to the Voellmy model would be justified if one can show that there is a clear advantage of using complex frictional models over simpler ones (Occam's razor). Comparison criteria (Brier skill score, Bayes factor, Akaike information, etc.) could help decide whether adding complexity is useful or not. When I see an empirical equation like Eq. (2), I wonder how a model involving 5 dissipation sinks can perform better than simpler models like the Coulomb or Voellmy ones. I suggest revising the introductory material, framing general and specific issues, and specifying the scientific issue(s) addressed by the paper.

ANSWER:

Probably the goals of the manuscript are not clear enough. The authors focus the work on analysing the effects of the Voellmy–model parameters and cohesion on the avalanche characteristics, and its effect on mass and momentum equations. After the referees comment, the objectives section of the document will be restructured, with the aim to making them clearer, highlighting the ultimate goal as follows: The main aim of this work is a detailed analysis of the effects of the friction terms of the Voellmy-model and a cohesion-model on the results of the numerical modelling of dense-snow avalanche dynamics. The analysis focuses mainly on the influence of the friction–cohesion model on the determination of the shear stresses, and their effects on mass and momentum. The relevance and influence of each term has been tested by comparing the numerical results with well-documented laboratory experiments and with a real case study. Simulations were performed using the numerical tool Iber (Bladé et al. 2014), a two-dimensional (2D) hydraulic model that has been recently enhanced to simulate dense-snow avalanches (Torralba et al. 2017). An additional aim of this work is to present the specific numerical treatment of the friction–cohesion model, that was implemented to adapt it to the particularities of the numerical scheme used by Iber: the Roe scheme (Roe 1986), which consists on the combination of the Godunov method together and the Roe Approximate Riemann Solver (Sanz-Ramos et al. 2020). The discussions on these numerical implementations and the understanding the role of the friction terms, together with some other considerations as the usage of nonhydrostatic pressure or nonisotropic properties, indicate that there is still a strong need for research on the description and modelling of the whole avalanche process (triggering, release, propagation, stopping, etc.). A last objective has been to provide contrasted data (numerical results) showing the final effects on the simulation of different avalanches (real and not) of variations in the involved parameters and procedures. This might provide criteria to modellers and avalanche risk analysis practitioners to better adjust the involved parameters and models options in some cases, or to decide on the need, or on the needlessness, of further parameter refinement, more detailed calibrations, or search for additional validation data. We also agree with the comments on there being no need for much complex models, and certainly, equation (2) shows a high degree of complexity is possible. Nevertheless, the document focuses in the Voellmy's model (Equation (5)) and not in all the possibilities underlying eq. (2). Regarding the friction models, certainly there are a lot of them, each one valid for the purposes that have been developed. Voellmy-fluid model is an empirical one, like other models in other fields, as for example sediment transport equations (Van Rijn, Meyer-Peter&Müller, Recking, etc.), and probably there are better ones, but it is widely used. Certainly, this model cannot reproduce the complex behaviour of the dense-snow avalanche dynamics. For this reason in Iber other friction models have also been included (Ruiz-Villanueva et al. 2019), widening its range of application, but this document is only focused in the Voellmy's and it being used for the simulation of dense-snow avalanches dynamics, thus the authors think that providing some information to assess its precision and uncertainties, as the role of the friction terms, can be helpful. On the other hand, the fact that in the Voellmy's model the friction terms are treated separately (solid phase and turbulent) has probably promoted it being used also for numerical modelling of granular flows also for other types of fluids than snow Hungr and McDougall (2009); Nam et al. (2019); Sartoris and Bartelt (2000); among others. Other approximations, as developed by Hutter, are also interesting (Hutter and Kirchner 2003). In order to clarify, Equation (2) only aims to show the theoretical different components of the shear stress, which could lead to much complex treatments of the frictional terms. Depending on the fluid behaviour, some shear stress terms can be more useful than others. This discretization is not analysed herein, and is neither implemented fully into Iber, being only the turbulent, the Mohr-Coulomb and the cohesion terms used for simulating the dense-snow avalanche in the model (Voellmy plus cohesion models). In this aspect, the authors have the feeling that among avalanche modellers there is a tendency to think that the Voellmy's model is especially adequate in this field (above other models), and that the commonly used parameters (from manuals and recommendations) are sometimes based on a consensus, perhaps based on legal reasons. As an additional objective, this work can give some light in showing that the parameters are not so unmovable (similar results can be obtained with different combinations) but also help in their determination as guidelines on the effects of each them are provided. The cohesion model recently proposed by Bartelt et al. (2015), Equation (6), has been included in the analysis because it as an additional friction term that can help to dissipate more energy and stop the avalanche, being cohesion an intrinsic property of the releasable snow. However, the model can work without considering cohesion terms (see Case 1, Section 3.2).

COMMENT:

Section 2 needs refinement. The underpinning assumptions and governing equations should be clearly introduced. For instance, do the authors use a Cartesian frame? Curvilinear coordinates? The numerical algorithm used for solving the Saint-Venant equations should be written by keeping mind that the NHESS normal reader may not be familiar with Roe solvers. How the source term is taken into account or how the dry/wet limit is implemented needs to be fully specified.

ANSWER:

Due to the aims of the manuscript, in the original manuscript the numerical aspects of Iber were only briefly described, in Section 2.2, but highlighting the main differences with other numerical tools. We can find a similar criteria in other publications of NHESS (Ferrari et al. 2020; Franz et al. 2020; Kang and Kim 2019). The authors only want to remark the most important changes in the numerical scheme (Line 112), showing the benefits of using it against other methods. Nevertheless, below we add some extra information and description of the model, that will be includes, as far as it is possible for length and reading flux reasons, to the final document. Iber is a hydraulic numerical modelling tool that solves the 2D-SWE using the Finite Volume Method (FVM) in Cartesian framework. It uses an upwind first order Godunov scheme, specifically the Roe scheme (Godunov Method with the Approximate Riemman Solver of Roe), for the convective flux. It also uses un upwind discretization for the geometric slope source terms (Vázquez-Cendón 1999) and a first order centred scheme for the other source terms. In the Roe scheme, the decomposition of the integral of the flow vectors is performed using the eigenvectors of the Jacobian matrix. The equilibrium between the flux vector and the bed slope contribution of the source term (through its decomposition as a linear combination of the eigenvectors) allows avoiding spurious oscillations of the free surface when the geometry is complex (Bladé et al. 2012a; b; Bladé and Gómez-Valentín 2006; Brufau et al. 2002; LeVeque 2002; Toro 2009). With the Voellmy's model, an upwind scheme has been used for the friction terms of the solid-phase and the cohesion, which conceptually can be assimilated as an opposite to the slope step, which decelerates the flow when moving, or counterbalances the gravity forces when stopped (see Figure 1). The integration of the terms of solid friction and cohesion as part of the bottom slope terms can be interpreted as a “friction slope (Sanz-Ramos et al. 2020a). The model uses the algorithm for the wet-dry front presented in Cea et al. (2007). The εwd parameter defines the fluid depth threshold below which a finite volume (cell) is considered to be dry. When the fluid depth in a cell is lower than the threshold ($h < \varepsilon$wd), the finite volume is considered to be dry. The numerical treatment of εwd only affects the computation of the mass and momentum fluxes, being the free surface and the flow velocity equal to zero when the bed elevation is higher than the free surface elevation (Cea and Bladé, 2015). This algorithm can successfully be used in finite volume schemes and ensures zero mass error (Brufau et al. 2004) . More information on the numerical scheme details can be found in the referenced bibliography (Bladé et al. 2012a; b, 2014b; Bladé and Gómez-Valentín 2006; Brufau et al. 2002; Cea and Bladé 2015; LeVeque 2002; Sanz-Ramos et al. 2020; Tan 1992; Toro 2009; Vázquez-Cendón 1999).

COMMENT:

Section 3 presents 3 case studies, and among them only the last one concerns a real-world avalanche. It would be interesting to include further comparison with well-documented avalanches, e.g. those monitored at La Sionne, Col du Lautaret, or Ryggfonn. Using high-resolution data (including front position over time, velocities, depth, etc.) would be useful to test Iber. A recent example of how field data can be used to deduced friction parameters is given by Heredia, M.B., N. Eckert, C. Prieur, and E. Thibert, Bayesian calibration of an avalanche model from autocorrelated measurements along the flow: application to velocities extracted from photogrammetric images, Journal of Glaciology, 1-13, 2020.

ANSWER:

The authors want to thank the referee to provide some well-documented real cases to compare it in deep with the simulated results from Iber. However, a deeper comparison with real data is far from the aims of the manuscript, which is focussed in analysing the friction parameters. The authors will consider those real cases for future works.

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COMMENT:

Section 4 contains overly general considerations on avalanche modelling. By focusing on a well-defined issue, applying Iber to several field cases, and discussing how prediction is improved by increasing the number of frictional parameters and how each frictional model performs relative to others would help beef up the discussion and dissipate the impression of rambling considerations.

ANSWER:

Section 4 mainly aims to discuss some aspects, not enough considered previously, about of the limitations of the model because some of its hypothesis, either in the equations themselves or in the friction model, and how some further developments can improve the model's behaviour like consideration of non-hydrostatic pressure; more complex friction models (adding cohesion); and its implication on hazard assessment. All these aspects are related with the referee comment described in the Major comments. We think that the theoretical development and test cases show and clarify these aspects. The application to several field cases could be interesting, and as the flow behaviour is improved in the test cases, it will also be improved to the first ones. Nevertheless, due to the geometric simplicity and the no need of calibration, the last can help in better resenting and showing the discussed aspects.

COMMENT:

I took a look at iberaula. I found the mention to Iber avalanche, but there is no information about the status of this code. Will it be available like Iber? Or reserved for collaborators, buyers, etc.?

ANSWER:

The version for simulating dense-snow avalanches is not available to the public because it is currently under development. In this sense and before to open to the experts the avalanche module, our contribution also aims to show that Iber can simulate snow avalanches as well as other numerical models; as a first step, we focussed on analysing the friction parameters and how they behave in Iber. As said before, a deeper comparison with real data is far from the aims of the manuscript. The authors will consider those real cases for future works. Nevertheless, as already happens with other modules under development, the authors welcome collaboration with other researchers and institutions. Iber is a final modelling tool for anybody to use it, but it is also an instrument for several research groups to be able to develop or test their own codes or methods, on the basis of an already existing framework. Collaboration, which is always welcome, may imply sharing the existing code, or just using it. As has already happened with other modules of Iber, once its robustness is proven, the module be freely distributed.

Specific comments:

PREVIOUS NOTE: the authors maintain the comments numbering used by the referee to answer it, and, in brackets, the corresponding line number of the PDF original manuscript.

COMMENT:

L9: You probably confuse “Voellmy friction” and “Voellmy-Salm(-Gubler)” model. The latter is a computational method for estimating velocities and runout distances (the avalanche is assumed to behave like a sliding block experiencing Voellmy friction. The avalanche path is split into different parts, and on each part, the momentum balance equation is solved to provide the steady-state velocity.) See Salm, B., A. Burkard, and H. Gubler, Berechnung von Fliesslawinen, eine Anleitung für Praktiker mit Beispielen, Eidgenössisches Institut für Schnee- und Lawinenforschung (Davos), 1990. (Hansueli Gubler translated it into English or provided an English summary, if needed).

ANSWER:

We used the notation “Voellmy-Salm” wrongly following similar notations found in some literature. We will corrected it accordingly in the final document, and thank the reviewer for such clarification.

COMMENT:

L28: I do not think that the Voellmy model is a “popular model” in the modelling of granular flows. It has mainly been used to model snow avalanches, and to a lesser extent debris flows.

ANSWER (L32):

Probably this model is not the most popular model for debris flows, nevertheless there are several numerical tools that use this approach, including case studies with a reasonable fitting: Hürlimann, M., Rickenmann, D., Medina, V., and Bateman, A. (2008). “Evaluation of approaches to calculate debris-flow parameters for hazard assessment.” Engineering Geology, Elsevier B.V., 102(3–4), 152–163. Schraml, K., Thomschitz, B., Mcardell, B. W., Graf, C., and Kaitna, R. (2015). “Modeling debris-flow runout patterns on two alpine fans with different dynamic simulation models.” Natural Hazards and Earth System Sciences, 15(7), 1483–1492. Medina, V., Hürlimann, M., and Bateman, A. (2008). “Application of FLATModel, a 2D finite volume code, to debris flows in the northeastern part of the Iberian Peninsula.” Landslides, 5(1), 127–142. Scheidl, C., Rickenmann, D., and McArdell, B. W. (2013). “Runout Prediction of Debris Flows and Similar Mass Movements.” Landslide Science and Practice, Springer Berlin Heidelberg, Berlin, Heidelberg, 221–229. Rickenmann, D., Laigle, D., McArdell, B. W., and Hübl, J. (2006). “Comparison of 2D debris-flow simulation models with field events.” Computational Geosciences, 10(2), 241–264. Nam, D. H., Kim, M. Il, Kang, D. H., and Kim, B. S. (2019). “Debris flow damage assessment by considering debris flow direction and direction angle of structure in South Korea.” Water (Switzerland), 11(2), 1–16. Hungr, O., and McDougall, S. (2009). “Two numerical models for landslide dynamic analysis.” Computers and Geosciences, Elsevier, 35(5), 978–992.) The authors indicated some of them in the manuscript (Hussin et al. 2012; Pirulli and Sorbino 2008;

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Schraml et al. 2015), but nevertheless the final manuscript will be corrected accordingly to the reviewer's comment and the word "popular" will be dropped.

COMMENT:

L42: what do you mean with the effects of friction being ignored? Can you be more specific when you state that the parameters are nonphysical.

ANSWER:

The values of the frictional parameters of the Voellmy model have been widely discussed in the literature, there are even guidelines that can help, as the referee indicates, for "untrained practitioners" to choose them. Some of these values have been have been considered to be adequate because they provided good enough results for the purposes of a particular case study (e.g. snow avalanches in Alps), and in many cases further analysis of them, calibration, or even questioning if a certain value could be possible, has been subsequently omitted. These parameters should be within the range of application of the empirical equation, but as denoted in Section 3.1, and particularly with the case study presented herein, there can a wide range of parameters that provide similar solutions. Which one or which combination are the best? Why we choose ones instead others? How is the effect of basing the model on an adaptation of the SWE? These are the reasons we wanted to express with the sentence "[. . .] the effects of the friction model on the individual terms of the equations are commonly ignored [. . .]", but probably a better and more clarifying expression can be found. This line will be rewritten accordingly in the final version after all revisions and discussions, in order to make the message clearer. We differentiate between physical and non-physical based parameters of the equations, being the first those that can be a measurable property of the material and the latter the rest of parameters. Thus, the Coulomb friction coefficient (μ) and the cohesion (C) can be considered two physically-based parameters that depend on the snow properties (Bartelt et al. 2015). But, we consider the turbulent friction coefficient (ξ) to be a non-physically based parameter.

In this line, the work of Fischer et al. (2015), shows an interesting analysis on this respect, suggesting that the effect of the turbulent friction coefficient is negligible for high values, in agreement with the results presented herein. This meaning of “physical” and “non-physical” will also be clarified in the updated manuscript that will be prepared after all the reviewers’ revisions and discussions.

COMMENT:

L49 a number of words (e.g. retention, detention, accretion, premise) throughout the paper seem to be used out of context.

ANSWER:

The above-mentioned words are used in the following parts of the manuscript: L49, the word retention is in “[. . .] Additionally, Bartelt et al. (2015) proposed the inclusion of an additional friction term related to snow cohesion, a real physical snow property, which has an effect of retention and can stop the avalanche irrespective of the maximum momentum reached during the avalanche propagation [. . .]”, and means that the cohesion is a property that can maintaining it aggregate, providing an “extra” force for holding it against the motion. L 59, the word detention is in “[. . .] The discussions on these numerical implementations, together with some other considerations like the usage of nonhydrostatic pressure or nonisotropic properties, indicate that there is still a strong need for research on the description and modelling of the whole avalanche process (triggering, release, motion, detention, etc.). [. . .]”, and means the process of the stop of the avalanche. We will change for the word “deposition”. L233, the word accretion is in “[. . .] An accretion of ðİIJŔðİŘű with âĎŐ can be observed, more accentuated for lower values of âĎŐ; and a linear diminution of the shear stress, regardless of the flow depth, while ðİIJĞ increases [. . .]”, and means an increment. We will change for the word “increment”. L394, the word premise is in “[. . .] For water, the 2D-SWE usually assume a hydrostatic and isotropic pressure distribution (Chaudhry, 2008). This means a linear variation in the vertical direction with the specific weight of the flow and the same in all horizontal directions. However, for non-Newtonian flows and steep slopes, this premise cannot be realistic (Ruiz-Villanueva et al., 2019). [. . .]", and it refers to the assumption of a hydrostatic and isotropic pressure distribution. We will change for the word "assumption".

COMMENT:

Eq. (1) why do you use the delta symbol instead the partial differential operator. F is the flux function, not a tensor. And in Eq. (3) you do not show F, but its gradient.

ANSWER:

In order to clarify the equation's notation, this part will be re-written following the most commonly notation used for 2D-SWEs, which in compact conservation form with source terms are:

(see Fig1.png)

where U is the conserved variable vector, F and G are the x and y components of the flow vector, and H is the source term. Momentum equations contain the gradients of the pressure and inertia terms (through the flow vectors F and G), the bottom slope and friction terms (through the source term H):

(see Fig2.png)

where h is the flow depth, v_x and v_y are the two velocity components, g is the gravitational acceleration, S_(o,x) and S_(o,y) are the two bottom slope components, and S_(rh,x) and S_(rh,y) are the two components of the rheological model. For water flows, the K_p factor is equal to 1 (hydrostatic pressure), and E is the a variation rate of the fluid column at a specific point, for example, a source or a sink in an open channel (Bladé et al. 2019), the rainfall/infiltration in hydrological modelling (Cea and Bladé 2015b), or the snow entrainment for avalanches (Eglit and Demidov 2005).

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L85: including snow entrainment into the governing equations involves modifying not only the mass balance equation, but also the momentum equation. See for instance Iverson Ouyang (Entrainment of bed material by Earth-surface mass flows: review and reformulation of depth-integrated theory, Reviews of Geophysics, 53, 27-58, 2015) for a correct treatment of this problem. Many avalanche-dynamics models involving snow entrainment and deposition are inconsistent from the continuum mechanics viewpoint. The problem is complex (see Issler, D., Dynamically consistent entrainment laws for depth-averaged avalanche models, Journal of Fluid Mechanics, 759, 701-738, 2014; Ancey, C., and B.M. Bates, Stokes' third problem for Herschel-Bulkley fluids, Journal of Non-Newtonian Fluid Mechanics, 243, 27-37, 2017. Lusso, C., F. Bouchut, A. Ern, and A. Mangeney, A free interface model for static/flowing dynamics in thin-layer flows of granular materials with yield: simple shear simulations and comparison with experiments, Applied Sciences, 7 (4), 386, 2017.

ANSWER:

The authors know about this problem, but in this document, this aspect is only mentioned in the introduction and it has not been considered in the numerical simulations presented herein. Certainly, the entrainment of new snow, which has lower momentum, slows down the flux of the bulk. In the Conclusions section, we remark some aspects that still need improvements, as the treatment of the entrainment. We have already started working in including snow entrainment in our model through a Master Thesis (Jordi Castelló i Sant 2020), and we'd like to thank the reviewer for the provided references and the indications, a very useful information for future works.

COMMENT: Section 2.2: this section should describe the numerical methods more clearly. As the model uses the same numerical framework as Iber, it should focus on the papers by Bladé and Cea for the homogeneous equation, and describe more clearly how the source term is taken into account to correct the solution to the homogenous equation.

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ANSWER:

A more detailed description of the numerical scheme used in Iber, including the treatment of the homogeneous equation is described in Answer 2 of the “Major comments”. We will modify the final manuscript accordingly maintaining the aims and reading flux of the document. Adding a very detailed description of the numerical aspects could probably confuse the reader and make the document not clear. The provided references can be used for further information on those aspects.

COMMENT:

L190 probably better to place the information on the numerical parameters elsewhere.

ANSWER:

We considered to include the numerical parameters in Section “2 Material and Methods”, particularly in Section 2.3, because it is here where there is a general description of the Case study, particular characteristics, geometrical description and, also, the numerical discretization used in all cases. The authors think that that warrants the reading flux.

COMMENT:

L209: Platzer measured the friction forces in a chute. There is no clear evidence that on a larger scale, the friction coefficient holds the same value (in the same way, in a granular packing, there is a weak link between particle friction and bulk friction).

ANSWER:

Certainly, Platzer measured this parameter in a chute with real snow, or at least coming from it. However, it should be expected the Coulomb friction stress (μ) to have limits, because it is a property of the snow. Release of dense-snow avalanches is impaired for high values of μ. Probably, as suggested by Bartelt et al. (2012), this parameter is a function of other parameters, but, deepening in this fact would include more complexity to a very complex problem, and beyond the scopes of the work.

COMMENT:

L269 what do you mean with “a 2D model in the vertical”.

ANSWER:

With this expression we colloquially use we meant a “2D depth-averaged model”, in which the depth averaging is performed “in the vertical” in comparison with 2D models that are averaged “in the horizontal” or in the flow width, as for example CE-QUAL 2D used in reservoir. In the final manuscript we will use the standard, and appropriate, expression “2D depth-averaged model”.

COMMENT:

L366 if the wet-dry limit is important, why do you mention it just here?

ANSWER (L367):

The authors want to remark relevance of the wet-dry threshold when dealing with numerical modelling of snow avalanches without distorting the reading of the manuscript. The wet-dry parameter is introduced firstly where the Case Studies are presented (Section 2.3), and further explanation and discussion about this parameter is in the Section 4 (Discussion).

COMMENT:

L420: the largest difference between simulated and real-world avalanches is that in the real world, an avalanche release is not like a dam break, in which a wall is suddenly removed. Initial rigidity or cohesion is probably a second-order problem, which does not influence the bulk dynamics significantly at later times.

ANSWER:

The authors totally agree that avalanches, at initial time steps, do not behave as a dam break. There are a great variety mechanisms that triger snow motion and approaches for their modelling, as precisely stated by the reviewer in some works (Ancey and Bain 2015). Real slab avalanches, for example, tend to have a block-like behaviour during the first time steps, disaggregating partially or completely after they have travelled some distance. This is precisely why the authors suggest a correction on the pressure terms through the parameter Kp, in order to make the results differ from those of a dam break. In a dam brake, pressure in the wet side of the front push water towards the dry side, with more pressure at the bottom of it, leading to the characteristic and well-known shape that water takes in that case. Limiting the pressure terms might improve this behaviour and make the results similar to those of dense snow. It is also true that the larger the internal cohesion of the snow layer, the more block-like behaviour the avalanche will have in its initial steps, but this cohesion can be lost immediately after the release and become less relevant for the bulk dynamics as commented by the reviewer. All this does not have a relevant influence on the global avalanche runoff, but using a 2D-SWE based model, the consideration of non-hydrostatic anisotropic pressure distribution can help in representing this block-like (or non-dam break like) behaviour. Anyway, as stated in the document, from our view point, more research is needed to couple avalanche triggering-release and motion, as for example the works of Gaume et al. (2019). Nevertheless, we will update the section of the article with some of these considerations.

COMMENT: L522: throughout the paper you have used ‘physical’ and ‘non-physical’, but these terms can be understood differently. You should be more specific.

ANSWER (L523):

The authors use this distinction in order to refer the parameters that are measurable, as for example the Coulomb friction (μ), in comparison with non-measurable parameters, as for example the turbulent coefficient (ξ), or criteria, as the fact to stop the avalanche using a momentum criteria (Bartelt et al., 2017). To clarify that, in the final manuscript this will be clarified accordingly.

REFERENCES

Ancey, C., and Bain, V. (2015). “Dynamics of glide avalanches and snow gliding.” Reviews of Geophysics, 53(3), 745–784. Bartelt, P., Bühler, Y., Buser, O., Christen, M., and Meier, L. (2012). “Modeling mass-dependent flow regime transitions to predict the stopping and depositional behavior of snow avalanches.” Journal of Geophysical Research: Earth Surface, 117(1), 1–28. Bartelt, P., Valero, C. V., Feistl, T., Christen, M., Bühler, Y., and Buser, O. (2015). “Modelling cohesion in snow avalanche flow.” Journal of Glaciology, 61(229), 837–850. Bladé, E., Cea, L., Corestein, G., Escolano, E., Puertas, J., Vázquez-Cendón, E., Dolz, J., and Coll, A. (2014). “Iber: herramienta de simulación numérica del flujo en ríos.” Revista Internacional de Métodos Numéricos para Cálculo y Diseño en Ingeniería, CIMNE (Universitat Politècnica de Catalunya), 30(1), 1–10. Bladé, E., and Gómez-Valentín, M. (2006). Modelación del flujo en lámina libre sobre cauces naturales. Análisis integrado en una y dos dimensiones. Centro Internacional de Métodos Numéricos en Ingeniería. Monografía CIMNE no 97, Junio 2006. Bladé, E., Gómez-Valentín, M., Dolz, J., Aragón-Hernández, J. L., Corestein, G., and Sánchez-Juny, M. (2012a). “Integration of 1D and 2D finite volume schemes for computations of water flow in natural channels.” Advances in Water Resources, 42, 17–29. Bladé, E., Gómez-Valentín, M., Sánchez-Juny, M., and Dolz, J. (2012b). “Source term treatment of SWEs using the surface gradient upwind method.” Journal of Hydraulic Research, 50(4), 447–448. Bladé, E., Sanz-Ramos, M., Dolz, J., Expósito-Pérez, J. M., and Sánchez-Juny, M. (2019). “Modelling flood propagation in the service galleries of a nuclear power plant.” Nuclear Engineering and Design, 352, 110180. Brufau, P., García-Navarro, P., and Vázquez-Cendón, M. E. (2004). “Zero mass error using unsteady wetting–drying conditions in shallow flows over dry irregular topography.” International Journal for Numerical Methods in Fluids, John Wiley & Sons, Ltd., 45(10), 1047–1082. Brufau, P., Vázquez-Cendón, M. E., and García-Navarro, P. (2002). “A numerical model for the flooding and drying of irregular domains.” International Journal for Numerical Methods in Fluids, 39(3), 247–275. Cea, L., and Bladé, E. (2015a). “A simple and efficient unstructured finite volume scheme for solving the shallow water equations in overland flow applications." Water Resources Research, 51(7), 5464–5486. Cea, L., and Bladé, E. (2015b). "A simple and efficient unstructured finite volume scheme for solving the shallow water equations in overland flow applications." Water Resources Research, 51(7), 5464–5486. Cea, L., Puertas, J., and Vázquez-Cendón, M. E. M.-E. (2007). "Depth averaged modelling of turbulent shallow water flow with wet-dry fronts." Archives of Computational Methods in Engineering, Springer, 14(3), 303–341. Eglit, M. E., and Demidov, K. S. (2005). "Mathematical modeling of snow entrainment in avalanche motion." Cold Regions Science and Technology, 43(1–2), 10–23. Ferrari, A., Dazzi, S., Vacondio, R., and Mignosa, P. (2020). "Enhancing the resilience to flooding induced by levee breaches in lowland areas: a methodology based on numerical modelling." Natural Hazards and Earth System Sciences, 20(1), 59–72. Fischer, J. T., Kofler, A., Fellin, W., Granig, M., and Kleemayr, K. (2015). "Multivariate parameter optimization for computational snow avalanche simulation." Journal of Glaciology, 61(229), 875–888. Franz, M., Jaboyedoff, M., Mulligan, R. P., Podladchikov, Y., and Take, W. A. (2020). "An efficient two-layer landslide-tsunami numerical model: effects of momentum transfer validated with physical experiments of waves generated by granular landslides." Natural Hazards and Earth System Science. Gaume, J., van Herwijnen, A., Gast, T., Teran, J., and Jiang, C. (2019). "Investigating the release and flow of snow avalanches at the slope-scale using a unified model based on the material point method." Cold Regions Science and Technology, Elsevier, 168(June), 102847. Hungr, O., and McDougall, S. (2009). "Two numerical models for landslide dynamic analysis." Computers and Geosciences, Elsevier, 35(5), 978–992. Hussin, H. Y., Quan Luna, B., Van Westen, C. J., Christen, M., Malet, J. P., and Van Asch, T. W. J. (2012). "Parameterization of a numerical 2-D debris flow model with entrainment: A case study of the Faucon catchment, Southern French Alps." Natural Hazards and Earth System Science, 12(10), 3075–3090. Hutter, K., and Kirchner, N. (2003). Dynamic Response of Granular and Porous Materials under Large and Catastrophic Deformations - Lecture Notes in Applied and Computational Mechanics Volume 31. Jordi Castelló i Sant. (2020). "Enhancement and application of numerical methods

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for snow avalanche modelling." Universitat Politècnica de Catalunya. Kang, S., and Kim, B. (2019). "Effects of coupled hydro-mechanical model considering two-phase fluid flow on potential for shallow landslides: a case study in Halmidang Mountain, Yongin, South Korea." Natural Hazards and Earth System Sciences. LeVeque, R. L. R. J. (2002). Finite Volume Methods for Hyperbolic Problems. Cambridge Texts in Applied Mathematic, Cambridge Univ. Press, Cambridge. Nam, D. H., Kim, M. Il, Kang, D. H., and Kim, B. S. (2019). "Debris flow damage assessment by considering debris flow direction and direction angle of structure in South Korea." Water (Switzerland), 11(2), 1–16. Pirulli, M., and Sorbino, G. (2008). "Assessing potential debris flow runout: A comparison of two simulation models." Natural Hazards and Earth System Science, 8(4), 961–971. Roe, P. L. (1986). "A basis for the upwind differencing of the two-dimensional unsteady Euler equations." Numerical Methods for Fluid Dynamics II, K. W. Morton and M. J. Baines, eds., 59–80. Ruiz-Villanueva, V., Mazzorana, B., Bladé, E., Bürkli, L., Iribarren-Anacona, P., Mao, L., Nakamura, F., Ravazzolo, D., Rickenmann, D., Sanz-Ramos, M., Stoffel, M., and Wohl, E. (2019). "Characterization of wood-laden flows in rivers." Earth Surface Processes and Landforms, 44(9), 1694–1709. Sanz-Ramos, M., Bladé, E., Torralba, A., and Oller, P. (2020a). "Las ecuaciones de Saint Venant para la modelización de avalanchas de nieve densa." Ingeniería del agua, 24(1), 65–79. Sanz-Ramos, M., Bladé, E., Torralba, A., and Oller, P. (2020b). "Las ecuaciones de Saint Venant para la modelización de avalanchas de nieve densa." Ingeniería del agua, 24(1), 65–79. Sartoris, G., and Bartelt, P. (2000). "Upwinded finite difference schemes for dense snow avalanche modeling." International Journal for Numerical Methods in Fluids, 32(7), 799–821. Schraml, K., Thomschitz, B., Mcardell, B. W., Graf, C., and Kaitna, R. (2015). "Modeling debris-flow runout patterns on two alpine fans with different dynamic simulation models." Natural Hazards and Earth System Sciences, 15(7), 1483–1492. Tan, W. . (1992). Shallow Water Hydrodynamics. Elsevier Science. Toro, E. F. (2009). Riemann Solvers and Numerical Methods for Fluid Dynamics. Springer Berlin Heidelberg, Berlin, Heidelberg. Torralba, A., Bladé, E., and Oller, P. (2017). "Implementació d'un model bidimensional per a simulació d'allaus de neu densa.” V Jornades Tècniques de Neu i Allaus: Pyrenean Symposium on Snow and Avalanches, Ordino, Andorra. Vázquez-Cendón, M. E. M. E. (1999). “Improved Treatment of Source Terms in Upwind Schemes for the Shallow Water Equations in Channels with Irregular Geometry.” Journal of Computational Physics, Elsevier, 148(2), 497–526.

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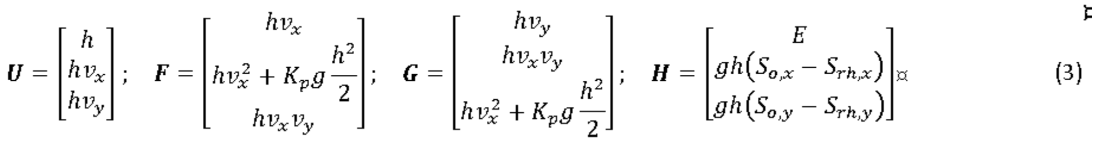
$$\frac{\partial}{\partial t}\boldsymbol{U} + \frac{\partial}{\partial x}\boldsymbol{F}(\boldsymbol{U}) + \frac{\partial}{\partial y}\boldsymbol{G}(\boldsymbol{U}) = \boldsymbol{H}(\boldsymbol{U})\text{¤} \qquad (1)^{\text{¤}}$$

Fig. 1.



$$\boldsymbol{U}=\begin{bmatrix} h \\ hv_x \\ hv_y \end{bmatrix};\quad \boldsymbol{F}=\begin{bmatrix} hv_x \\ hv_x^2+K_p g\dfrac{h^2}{2} \\ hv_x v_y \end{bmatrix};\quad \boldsymbol{G}=\begin{bmatrix} hv_y \\ hv_x v_y \\ hv_x^2+K_p g\dfrac{h^2}{2} \end{bmatrix};\quad \boldsymbol{H}=\begin{bmatrix} E \\ gh\left(S_{o,x}-S_{rh,x}\right) \\ gh\left(S_{o,y}-S_{rh,y}\right) \end{bmatrix} \qquad (3)$$

Fig. 2.

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