INFLUENCE OF DEM RESOLUTION AND DOMAIN DISCRETIZATION ON THE SNOW AVALANCHE DYNAMICS MODELLING

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ABSTRACT: Numerical modelling of snow avalanche dynamics requires necessarily the utilisation of terrain topography to update the elevation of the calculation meshFree distributed topographical data is currently available worldwide through digital terrain models (DTM), from coarse to fine resolutions. This work aims on investigating the influence of the DTM resolution, both in the horizontal and vertical accuracy, on the results of the bulk dynamics of dense snow avalanches. To that end, the numerical tool Iber, a depth-averaged hydrodynamic numerical tool recently enhanced for the simulation of non–Newtonian shallow flows such as snow avalanches, was used. Several calculation scenarios, based on two well-documented events, were carried out utilising combinations of different mesh sizes and DTMs. The findings reveal the importance of DTM resolution for mid-low size avalanches. When comparing identical mesh resolutions, the vertical precision of the DTM has a more significant impact on the avalanche dynamics than the horizontal resolution of the DTM. Even with a five-fold improvement in spatial resolution, which currently includes LiDAR techniques, the outcomes derived from the 5-meter DTM closely resembled those of the 2-meter DTM, the computational cost being reduced notably. LiDAR-based topographical data allows the generation of DTM and DEM (digital elevation models), being the latest useful to represent the obstructions on the flow dynamics due to the vegetation and providing a closest representation of the avalanche dynamics to the observations.

KEYWORDS: DTM/DEM, numerical modelling, Iber, smoothing, fill sinks.

1. INTRODUCTION

Snow avalanches are rapid flows of snow down a slope, posing significant risks to life, infrastructure, and ecosystems in mountainous regions (CCA, 2016; McClung et al., 2002). Understanding and predicting these events are crucial for effective risk management and mitigation strategies. Snow avalanche modelling is a scientific approach that aims to simulate the dynamics of avalanches to predict their behaviour, path, and potential impact areas. These models range from simple empirical formulas to sophisticated numerical simulations that consider various physical processes involved in avalanche initiation, flow, and deposition (Eglit et al., 2020).

A fundamental component of avalanche modelling is the integration of topographical data, which describes the terrain over which avalanches occur. Topography influences many aspects of avalanche dynamics, including the starting zone, flow path, and run-out distance (Maggioni and Gruber, 2003). Accurate topographical data, obtained from sources such as digital terrain/elevation models (DTM/DEMs), aerial photography, and satellite imagery, provides critical information about slope angles, aspect, curvature, and roughness, all of which are essential parameters in modelling efforts (Gruber and Haefner, 1995; Maggioni et al., 2013).

Topographical data allows for the detailed mapping of potential avalanche release areas and paths, enhancing the precision of avalanche hazard assessments. As computational technologies and remote sensing methods advance, the accuracy and reliability of avalanche models continue to improve, making them indispensable tools in the field of snow science and hazard management.

The current work explores the influence of the topographical data (*xy*-resolution and *z*-accuracy) and the domain discretization on the modelling of the avalanche dynamics. To that end, the numerical model Iber (Bladé et al., 2014) recently enhanced to simulate non–Newtonian shallow flows (Sanz-Ramos et al., 2024), such as dense snow avalanches (Sanz-Ramos et al., 2023c), was utilised to simulate several well-documented snow avalanche events. The simulations were carried out by considering five types of topographic data, together with particular options of Iber to improve the representation of the terrain.

2. MATERIALS AND METHODS

2.1 Study sites and events

Different study sites and avalanche events were chosen to analyse the influence of the topographical data in the snow avalanche dynamics, together with some procedures to enhance the elevation data in the numerical model. All study cases are located on the southern side of the Pyrenees range (Figure 1).

On January 2014 a slab avalanche occurred in Bonaigua valley, crossed a road and stopped few meters below with a runout distance of around 650 m. The avalanche split into branches at the deposition area. A wide description of the event besides data utilised in the numerical model is detailed in Sanz-Ramos et al. (2023b).

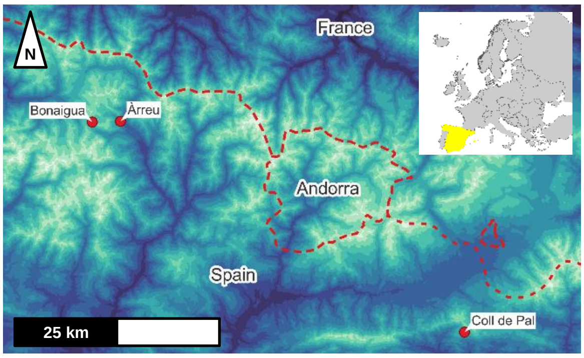

Figure 1: Location of the study sites.

On February 2018 an avalanche occurred near to Coll de Pal pass, between 1900 and 2200 m.a.s.l and stopped on a road and few meters below. The event was characterized few days after the event showing a runout distance of 370 m with vertical drop of 215 m. A full description of the survey and the numerical parameters are described in Sanz-Ramos et al. (2021b).

The last case study is the avalanche occurred in in 1996 in Bordes d'Àrreu, a small village that was partially destroyed in 1803 by another avalanche event (Oller et al., 2020).

2.2 Topographical data

All topographical data utilised come from the Institut Cartogràfic i Geològic de Catalunya (ICGC, 2021), who provide DTMs of different horizontal and vertical resolutions and LiDAR data, among other products.

The DTM of 15x15m and 5x5m of cell size are generated from the topographical base at 1:5000 scale. The 2x2m of cell size DTM is based on the 2nd version of LiDAR. Finally, the cloud of points come from LiDAR data, being the 1st version obtained from 2008 to 2011 while the 2nd version from 2016 to 2017. LiDAR data were filtered aiming to obtain the ground, key points and, when is necessary, the vegetation (from low to high height), and then converted into a DTM or DEM in raster format.

Table 1 summarizes the main specifications of the topographical data employed to update the elevations of the mesh at each numerical model.

Table 1. Specifications of the topographical data.

Name	Resolution	Accuracy	Source
DTM15x15	15m	0.90m	1:5000
DTM5x5	5m	0.90m	1:5000
DTM2x2	2m	0.15m	LiDAR
LiDARv1*	0.5p/m^2	0.06m	LiDAR
LiDARv2*	0.5p/m^2	0.06m	LiDAR

**With and without vegetation.*

2.3 Numerical tool: Iber

The case studies were simulated with Iber (Bladé et al., 2014), a free distributed two-dimensional hydrodynamic tool recently enhanced to simulate non–Newtonian shallow flows such as dense snow avalanches, mudflows, lahars, wood laden flows, etc. (Ruiz-Villanueva et al., 2019; Sanz-Ramos et al., 2023b, 2023c, 2024).

Iber solves the shallow water equations (2D-SWE) throughout a particular numerical scheme based on the Roe scheme (Roe, 1986). It ensures the balance between the flux and pressure gradients and the friction source term, avoiding numerical instabilities and achieving non–horizontal free surface according to the rheology of the fluid even in irregular geometries and sloping terrain (Sanz-Ramos et al., 2023c).

The characterization of the resistance forces can be done by means of different rheological models, such as Voellmy (1955) jointly or not with cohesion (Bartelt et al., 2015), simplified Bingham (Bingham, 1916; Chen and Lee, 2002; Naef et al., 2006), Manning (Chow, 1959), dilatant- and viscous-like (Macedonio and Pareschi, 1992), quadratic (O'Brien and Julien, 1988), and (Herschel and Bulkley, 1926). Based on previous studies, the Voellmy-Bartelt rheological model was utilized in the simulations.

Additionally, Iber includes several features oriented to improve the numerical performance of the model. Specially those for topographical data treatment in hydrological modelling (Cea and Bladé, 2015; García-Alén et al., 2022; Sanz-Ramos et al., 2020, 2021a), such as 'fill sinks' and 'smoothing' can be also useful for snow avalanche modelling.

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Briefly, the 'smoothing' option adjust the elevation of a node according to the nodes elevation of its vicinity; while the 'fill sinks' option increase the elevation of the depressed nodes to the top elevation of the surrounding to delete natural or unnatural depressions.

2.4 Scenarios and domain discretization

Several simulations were carried out per each study site by feeding the model with the original data, considering two filters of the topographical smoothing that Iber incorporates (2 and 10 passes) and the utilisation of DTM (no vegetation land cover) or DEM (vegetation land cover) in LiDAR based simulations. Thus, three simulations were done per each topographical source, except for LiDAR in which three additional simulations were carried out considering the 'fill sinks' option of Iber.

The domain was discretized by means of triangular elements, defining a side length equal to the resolution of the DTM in average. Thus, the element side ranges from 1 to 15 m.

3. RESULTS

Due to the large number of simulations, the most relevant results of the influence of the topographical data in the avalanche dynamics is presented.

3.1 Coll de Pal 2018

The parameters of the rheological model (Voellmy-Bartelt) were selected according to Sanz-Ramos et al. (2021b), being the turbulent coefficient of 1250 m/s^2, the Coulomb friction coefficient of 0.34, and the cohesion of 100 Pa.

Figure 2 shows the map of depth when the avalanche stopped. As expected, as the element size is reduced and therefore the accuracy of the topographic data is increased, the results fit more closely to what was observed (transparent white polygon).

The DTM15x15 provided coarse results due to the low resolution and accuracy of the topography and the size of the avalanche. A 5x5m DTM shown a good representation of the avalanche, with a detention area shifted to the east as observed. When a 2x2m resolution is utilised, the results adjusted to the observations, not only in the avalanche's extent but also in the snow accumulated on the road (Sanz-Ramos et al., 2021b). Models fed with LiDAR data also performed adequately, with differences in both scenarios related to vegetation growth (notably higher in LiDARv2 versus LiDARv1). In such cases, the shape of the vegetation was included in the mesh acting as an obstacle to the flow, generating accumulation upstream of the trees and expanding the detention zone (Naaim et al., 2004).

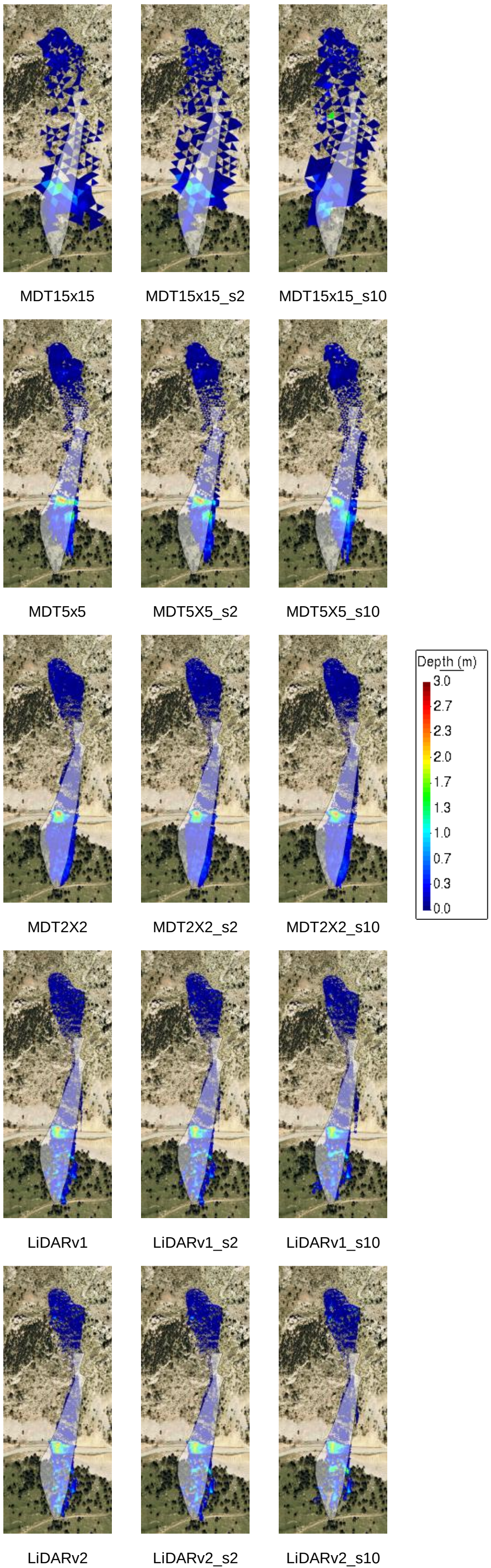

Figure 2: Coll de Pal. Map of depth when the avalanche stopped.

3.2 Bonaigua 2014

The study area was discretized in 3705 elements for the coarse DTM of 15x15, while the number of elements almost reach 750,000 for the LiDAR-based models. The parameters of the rheological model that best fit to the observations are 500 m/s^2 for the turbulent coefficient of and 0.125 for the Coulomb friction coefficient (Sanz-Ramos et al., 2023c).

This case highlights the benefit of using the 'fill sinks' (_fs) option of Iber since already exists some points of the LiDAR cloud with wrong elevation data despite the data have been treated previously. This generates unreal depressions on the terrain (Figure 3, upper) that, sometimes, are difficult to detect event using ad hoc LiDAR or/and GIS software.

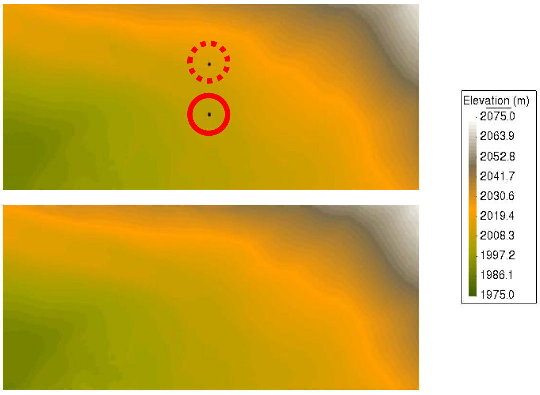

Figure 3: Bonaigua. Map of terrain: LiDARv1 (upper) and LiDARv1_fs (lower). Values lower that 1975 m are plotted in black, which represents the depression (highlighted in a circle).

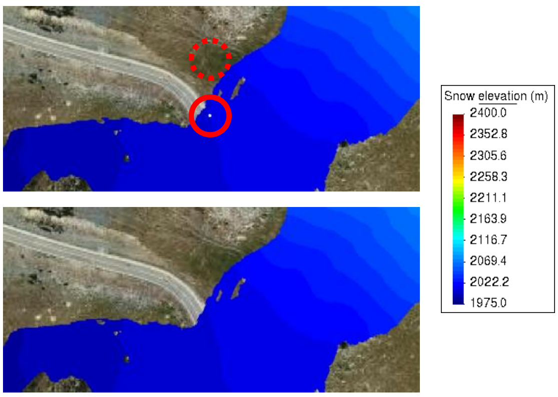

Figure 4: Bonaigua. Map of maximum snow elevation: LiDARv1 (upper) and LiDARv1_fs (lower). Values lower that 1975 m are represented in white (highlighted in a circle).

As expected, this abrupt change in the topography notably modified the dynamics of the avalanche because the depression tends to be filled. An unreal increase of velocity was produced due to the change of slope, while the depression could not be filled depending on the avalanche dynamics generating an unreal snow elevation profile (Figure 4, upper).

The 'fill sinks' option of Iber numerically fill these depressed areas, solving the aforementioned issues and providing a reliable snow avalanche dynamic modelling.

Regarding the performance of the model with the different topographical data, in all cases the results show a detention area split in two branches, even for the coarse DTM of 15x15m.

3.3 Àrreu 1996

The snow avalanche of Àrreu 1996 was well reproduced with all topographical data due to the size of the avalanche. The detention zone was produced in the Monars Gorge and Àrreu River junction. Figure 5 (upper maps) shows the avalanche at the end of the simulation when using a 15x15 (up), 5x5 (middle), and 2x2 (down) DTM.

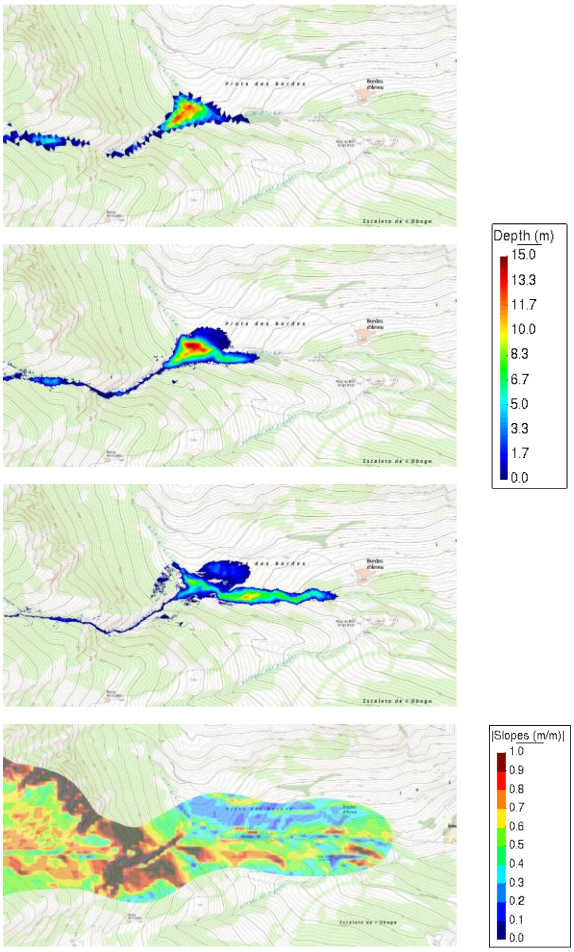

Figure 5: Àrreu. Map of depth when the avalanche stopped (upper maps). Map of slopes (lower map), coloured map filtered from 0 to 1 m/m (black colour represents slopes higher than 1 m/m).

This agrees with the selected rheological properties of the avalanche and the slope, the Coulomb friction coefficient being of 0.35 (Figure 5, low map).

As the DTM cell size is reduced, the definition of the junction, as well as the rest of the valley, improves, providing a more detailed and accurate description of the avalanche dynamics. The junction is almost perpendicular; thus, when the avalanche arrives tends to continue flowing in the original direction generating an accumulation at higher altitudes of the riverbed.

Àrreu case study also presented problem with the topographical data, especially in LiDAR data with some points below of the real topography. This issue was also solved with the ‘fill sinks’ option of Iber.

4. DISCUSSION

4.1 On the data source and performance

All data utilised come from current techniques and followed several standards that modellers utilise to feed numerical models aiming to simulate different environmental flows.

Particularly to dense snow avalanches, currently exists a wide range of resolutions thanks to the continuous evolution in the acquisition of topographical data. Finer resolution commonly implies higher accuracy, being this last factor a key in numerical modelling (Chojnacki et al., 2010; Dottori et al., 2013), especially in mountain areas where the accuracy is limited by the technique utilised to obtain it.

This also implies the possibility of building up more detailed numerical models. The study cases were discretised using a mesh of triangular elements, which it involves a density of elements per hectare ranging from ~88 to 20000. The computational effort when finer meshes are utilised increases notably for numerical models based on a numerical scheme explicit in time (Courant et al., 1967). Thus, the application of general-purpose computing on graphics processing units being mandatory to carry out simulations in a feasible computational time, such is already done in the hydrodynamic and sediment transport module of Iber (Dehghan-Souraki et al., 2024; Sanz-Ramos et al., 2023a) and it will be realized in future version of the non–Newtonian module, reaching speed-up above 100-times.

4.2 On the land cover (DEM vs. DTM)

LiDAR data is a cloud of points usually classified according to the LiDAR return/intensity as ground, low-mid-high vegetation, buildings, water, etc. Depending on the procedure to obtain this cloud of points, and later treatment, LiDAR data can be directly used to update the elevation of the nodes of a calculation mesh.

Figure 6 exemplifies the differences in the utilisation of topographical data as DTM (left, without vegetation land cover) and as DEM (right, with vegetation land cover) for the simulation of the event of Coll de Pal. In both cases the runout obtained was similar, but considerable differences were observed in the dynamic and static phases, specially below the road.

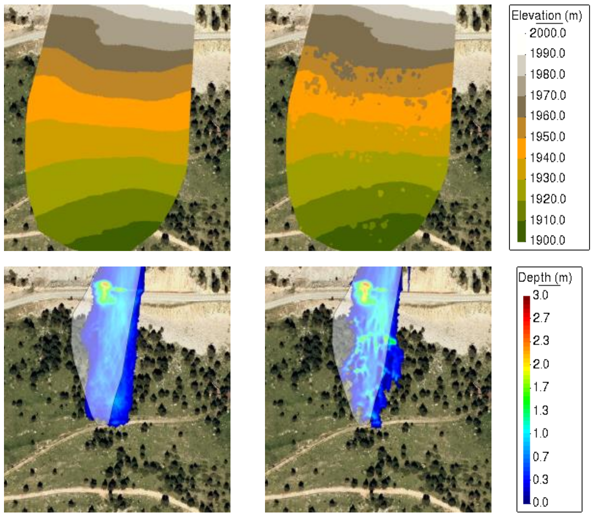

Figure 6: Coll de Pal event simulated with LiDARv1: DEM (upper left) and DTM (upper right); map of maximum depth with topographical data as DEM (lower left) and as DTM (lower right).

This area is covered by mid-low dense vegetation that corresponds to a relatively young forest. When the DEM is utilised, the vegetation is incorporated into the model as an additional elevation that acts as macro-roughness. This has an effect on the avalanche path and detention since flows with enough energy partially accumulates upstream of the vegetation; while the rest continue flowing generating an irregular detention zone in comparison with the DTM simulation, which is smooth. In such case, the results that best fit with the observation may be in an intermediate situation: DTM with vegetation in the greatest trees and an increase of roughness in the rest.

Considering the vegetation of the DEM in the snow avalanche modelling could not be representative of the real behaviour: the shrub vegetation is either covered with snow, or has a flexible behaviour towards the avalanche as occur in fluvial floods (Cheng, 2011; Nepf, 2012; Sanz-Ramos et al., 2018; Stephan and Gutknecht, 2002), and some trees will withstand the impact, but others will break. Thus, DEM data considers all these elements as a permanent and invariant macro-roughness throughout the simulation, not being as realistic as with DTM data. The use of

DEM can be more useful for small avalanches, which do not have enough energy to break trees, than for large avalanches, where there is a lot of forest destruction. However, further investigation is needed to fully understand the role of DEM in snow avalanche modelling.

4.3 *Fine-tuning topography with Iber*

Additionally, despite the classification and treatment of LiDAR data, which is done by the provider of the source following strict standards, some errors and outliers can remain. This was the case in Bonaigua case study, in which a few points of the cloud have an elevation very far from the points of its vicinity, even after applying the same treatment as for the rest of LiDAR data. In such cases, the 'fill sinks' options of Iber allowed to correct the topographical data filling the sink with an elevation equal to the lowest node of the surroundings. This is also useful to fill depressed areas that usually cumulates snow during snow events (e.g. upstream of bridges, culverts, etc.) and might condition the avalanche dynamics.

The option 'smoothing' of Iber plays a role similar to those obtained when simulating an avalanche with coarse DTMs. However, this option allows modellers to use very fine resolutions and obtain a smooth representation of the terrain, even when using summer topography. Further investigation on the utilisation of 'smoothing' of Iber is necessary, mainly oriented to compare the results of summer topography with 'smoothing' and the winter topography (Maggioni et al., 2013).

These option helps the modeller to deal, without additional treatments and in the simulation process, with some problems in the topographical data when simulating dense snow avalanches.

5. CONCLUSIONS

Several topographical sources were utilised to reproduce well-documented snow avalanche events with Iber, a depth-averaged hydrodynamic numerical tool recently enhanced to simulate non–Newtonian environmental flows.

Depending on the size of the avalanche, coarse mesh and topographical data (e.g. 15m) cannot be able to obtain a suitable reproduction of an avalanche event. Finer meshes and detailed topographical data, despite increase the computational effort, provide high resolution results. The utilisation of DEMs (DTMs with vegetation) can be utilised considering the vegetation as macro-roughness, especially for small and medium avalanches, but further research is needed.

A direct utilisation of DTM/DEMs of 15, 5, 2, and 1 m of raster cell size is possible, but some issues might be generated especially with LiDAR data. To that end, the options of Iber 'smoothing' and 'fill sinks' can help modellers to solve by generating a smoother topographical data and filling natural or unnatural depressed areas. This improves the simulation of the dynamics of the avalanche.

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