DAN3D MODEL PARAMETERS FOR SNOW AVALANCHE CASE STUDIES IN WESTERN CANADA

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ABSTRACT: Dynamic models are an important aspect of a snow avalanche hazard assessment for planning purposes. In this research, we analyzed the ability of the three-dimensional model Dan3D to back-analyze avalanche case studies. Dan3D is a depth-averaged model that calculates flow-like motion over three-dimensional topography and was developed to simulate the motion of extremely rapid, flow-like landslides. Twenty-seven snow avalanche case studies were analyzed. Most of the cases were from British Columbia and Alberta in western Canada and one was from the state of Washington. Each avalanche case had a field-observed runout with an average return period of approximately 100 years. For each case, the Voellmy rheology was used and the two parameters, including friction and turbulence coefficients, were calibrated to determine values that best simulated the observations. Friction coefficients varied from 0.15 to 0.35. Turbulence coefficients varied from 1000 to 4000 m/s^2. Models were run both with and without entrainment to assess variations in model parameters to best simulate the cases. Most cases could be modelled with reasonable runout lengths, lateral extents, and debris thicknesses. Friction and turbulence coefficients for avalanches within a certain mountain range and hence snowpack type were often similar. Although avalanche flow velocities were not available for most cases, they were within the range of those listed in other studies. Velocities were available for a case study from Norway, and modelled velocities were comparable to those observed. The results suggest that Dan3D is a capable modelling software package for performing dynamic modelling of snow avalanches.

KEYWORDS: dynamic model, avalanche runout, model calibration, entrainment.

1. INTRODUCTION

Dynamic models are used to estimate the runout and lateral extents, velocities, and impact pressures of snow avalanches. They are important for planning purposes, particularly in locations without strong evidence of snow avalanche extents from historical records or vegetation. Some of the earlier dynamic models are simple to use but only analyze flowing avalanches down a chosen path line, such as the PLK model (Perla et al., 1984), PCM model (Perla et al., 1982), and Leading Edge Model (McClung and Mears, 1995). Further, these simple models do not work well for complex terrain geometries. With advances in computers came more powerful dynamic models. Three-dimensional models, such as RAMMS (Christen et al., 2010) and Dan3D (Hungr and McDougall, 2009) have successfully simulated snow avalanche case studies (e.g., Wilbur et al., 2014; Aaron et al., 2016) and are being used in planning studies. RAMMS and Dan3D are similar in that they both use the Voellmy rheology to simulate the basal resistance.

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Although dynamic avalanche models are valuable for planning purposes in western Canada, confidence in the input parameters is generally low due to limited experience with the models. In this paper, we calibrate the dynamic model Dan3D using large and destructive snow avalanches in western Canada, with the goal of producing a dataset that increases our confidence in the input parameters.

Dan3D (Dynamic Analysis of Landslides in Three Dimensions) is a fluid mechanics-based model developed at the University of British Columbia to simulate the motion of extremely rapid, flow-like landslides (Hungr and McDougall, 2009). Dan3D is capable of simulating anisotropic internal stress states and entrainment of material during flow. The numerical method of smoothed particle hydrodynamics is used to solve the governing equations, which allows for the simulation of large displacements and bifurcations of the flow. The Voellmy rheology (Voellmy, 1955) was used for this study, which uses two parameters, a friction coefficient (μ) and a turbulence coefficient (ξ).

2. DATA AND METHODS

We simulated 27 snow avalanche case studies with Dan3D. Each avalanche had a runout length return period of approximately 100 years (i.e., between 30 and 300 years). All but one of the cases were from western Canada, with the other being from northern Washington state. For each case study, detailed information was obtained about the avalanche, such as measurements, witness notes, historical records, photographs, and videos. Most of the cases were obtained from operations, including Alberta Parks (Kananaskis Country Public Safety), British Columbia Ministry of Transportation and Infrastructure, and Parks Canada (Banff-Yoho National Parks and Glacier National Park). Table 1 highlights some of the characteristics of the cases.

Topographical data for the avalanche paths were obtained from the freely-available Aster2 digital elevation model (DEM) (Tachikawa et al., 2011) or the SRTM DEM (Farr et al., 2007). Both models have a spatial resolution of 1-arc second, or approximately 30 m. For three of the cases, LiDAR data with a 1 m spatial resolution and downsampled to 5 m were also used and compared to the results of the coarser model.

An evaluation of the importance of snow entrainment during avalanche flow was determined by expert witness observations and by a comparison of the estimated slab mass to the estimated deposit mass. Mass was used instead of volume due to measured or expected density variations between the slabs and deposits. Entrainment was allowed within the lower starting zone, track, and upper runout zone, which is referred to in Dan3D as the erodible zone. Entrainment was allowed for the top 0.5 m of the surface, which is approximately the average of entrainment depths observed in case studies by Sovilla et al. (2006). The entrainment rate, which is the bed-normal depth eroded per unit flow depth and unit displacement and further described by McDougall and Hungr (2005), was calculated based on the slab mass, deposit mass, and length of erodible zone. Case studies were calibrated both with and without entrainment enabled.

Table 1. Characteristics of the 27 case studies analyzed in this study. Values in brackets indicate how many of the cases are included in the listed characteristic.

Date Range	1989 to 2018
Mountain Range	Coast Mountains (8) Columbia Mountains (9) Rocky Mountains (10)
Trigger	Natural (19) Explosives (8)
Flow type	Dry (25) Wet (2)
Destructive size	Size 3 (5) Size 4 (19) Size 5 (3)
Slab thickness	Minimum: 0.7 m Average: 1.9 m Maximum: 4.0 m
Slab weak layer	Surface hoar (5) Facets (9) Depth hoar (13)
Slab volume	Minimum: 7,000 m^3 Average: 240,000 m^3 Maximum: 1,300,000 m^3
Deposit volume	Minimum: 9,000 m^3 Average: 770,000 m^3 Maximum: 8,000,000 m^3

The friction coefficient (μ) and turbulence coefficient (ξ) parameters were modified until the simulation best-fit the observed avalanche. This was based on a trial-and-error approach and by comparing results in a matrix-like format as described by McDougall (2017). The characteristics analyzed included the final deposit runout extent, lateral boundaries of flowing debris, final lateral extents, and deposit dimensions including thickness. Although it is possible to apply different parameters to sections of the path, only one value for each μ and ξ were applied to the entire path for simplicity and to allow for a comparison between different case studies. Since velocity profiles were not available as part of the calibration, it was possible to simulate similar spatial results with varying friction and turbulence coefficients. The maximum velocities were qualitatively analyzed and used to decide the best-fit.

A case study was also obtained from the Norwegian Geotechnical Institute (NGI), which included velocity data. This study was simulated in the same approach as the other cases and modelled velocities were compared to measurements.

3. RESULTS AND DISCUSSION

Dan3D reproduced the observed impact area for each case history. For all 27 case studies, the entrainment rate ranged between 0.0001 and 0.003 m^{-1}, with an average of 0.001 m^{-1}. When grouping the cases by mountain range (i.e., Coast Mountains, Columbia Mountains, and Rocky Mountains), the entrainment rate was generally highest for cases in the Rocky Mountains (Figure 1).

For simulations that included entrainment, the friction coefficient ranged between 0.15 and 0.35 with an average of 0.26. Without entrainment being applied, the friction coefficient ranged between 0.1 and 0.35 with an average of 0.22. When grouping the cases by mountain range, the highest friction coefficient values were often for the Coast Mountains (Figure 1). It is unclear if this is due to terrain differences, snowpack differences (e.g. warmer, maritime snow climate), or is strictly because of the small dataset. More cases are required to rigorously assess this. There was

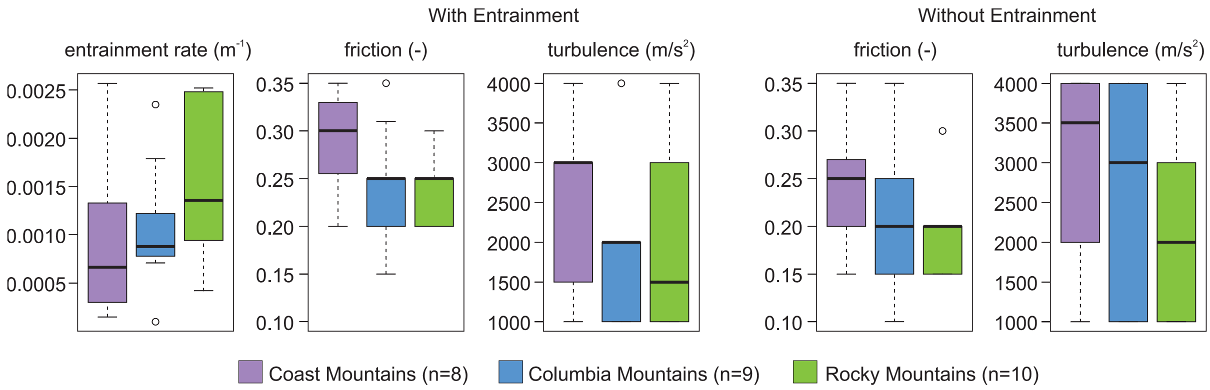

Figure 1. Calibrated parameter values for simulations with and without entrainment, grouped by mountain range in western Canada. For each boxplot, the black line indicates the median, boxes span the first and third quartiles, and whiskers span the lowest datum and the highest datum within 1.5 times the lower and upper quartiles, respectively. Outliers are displayed as open circles.

still a substantially large range observed within the data for each mountain range. For example, although the median for the Coast Mountains was higher than the other two regions, the minimum and maximum fell within the ranges of the other regions.

The turbulence coefficient ranged between 1000 and 4000 for all simulations, with an average of 2100 when entrainment was used and 2600 without entrainment. The highest median turbulence coefficient was for the Coast Mountains when grouping the cases by mountain range (Figure 1). This could be an artefact of the relatively small dataset, as the minimum and maximum values reach the spread of modelled turbulence coefficients.

The friction and turbulence coefficient values were comparable to those from other dynamic models, such as RAMMS. See Jamieson (2018) for a summary of parameter values often used in other dynamic models.

The large range of the friction and turbulence coefficients within mountain ranges indicates that there are no single parameter values that will properly simulate all the avalanches with a given return period in a region. This is due to the numerous important characteristics that govern the flow, such as variations in the terrain shape, snowpack, and water content of flowing avalanches. Instead, this study highlights variability of basal resistance parameters which can be used in a probabilistic manner. It also highlights the importance of using numerous methods for estimating avalanche characteristics for planning studies. It is possible that the variances of the coefficients within each mountain range may be reduced if velocity profiles were also available for calibration, allowing for more accurate parameter selection for each case. However, it is still likely that the variances would be high, and the distributions would appear similar to those found in this study due to the other important characteristics previously described.

Within Dan3D, modelled entrainment affects the simulated path of an avalanche in two ways. First, it can slow the overall debris because of inertial resistance; i.e., energy is applied to move the entrained material and incorporate it within the flow. Second, entrainment can increase deposit lengths because more material is available within the flow, and hence more spreading occurs. For the case studies, it is likely that the second point was dominant, allowing for the cases with entrainment to travel farther and spread wider than the same case without entrainment (Figure 2). Therefore, when entrainment was not used, friction parameters often had to be reduced and turbulence coefficients had to be increased to reach the same runout length and lateral spreading as when entrainment was applied. Additionally, Figure 1 shows that the variances of calibrated coefficients are reduced when entrainment is considered. This suggests that the effects of entrainment influence the value of the calibrated basal resistance parameters when entrainment is not explicitly accounted for.

The two cases that flowed as wet avalanches had a friction coefficient of 0.25 and 0.35 and a turbulence coefficient of 1000. The turbulence coefficient is at the low range of all the cases. This was predicted, as a low turbulence coefficient limits the amount of spreading of the debris, which is typically observed for wet avalanches. The friction coefficients are within the middle to high end of the range. Although only two cases were simulated, we expected to see relatively high friction coefficients due to their slower motion.

Comparing the runout distance and lateral extents of the simulated avalanches to field observations was most often used as the primary criteria for selecting the friction and turbulence coefficients, as the velocities and deposit thicknesses

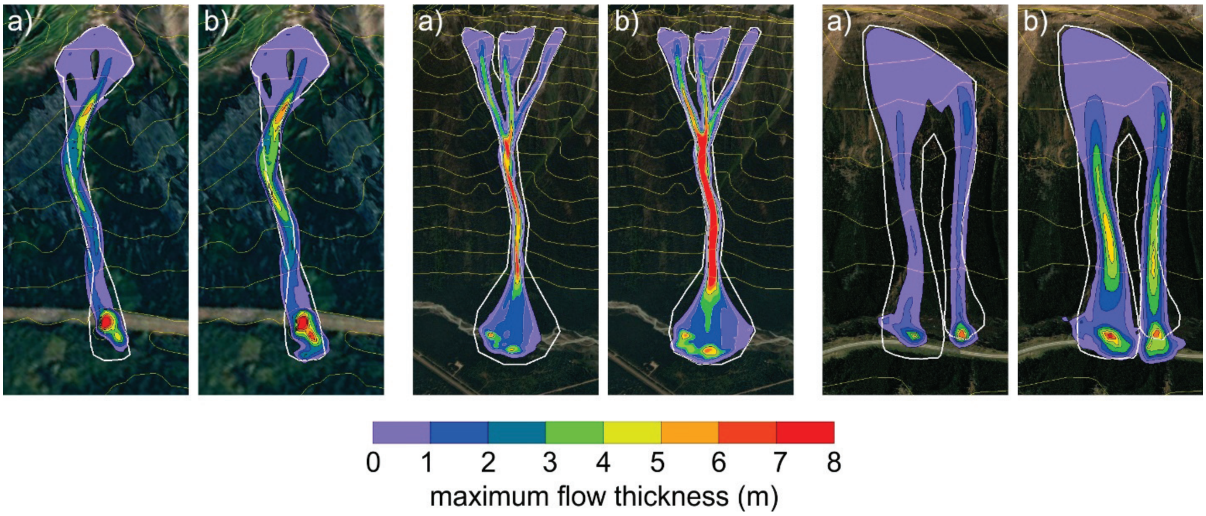

Figure 2. Three case study Dan3D outputs a) without entrainment and b) with entrainment, using the same friction, turbulence coefficient, topography, and slab dimensions. White outlines are observed flow boundaries. Thin yellow lines are 100 m elevation contours.

were typically estimated or not available. In general, the model results often matched the runout extent as well as the lateral extents when the runout zones were relatively uniform and fan-shaped. Some discrepancies occurred where the runout zones had irregular topography, such as narrow gullies. This is likely because the DEM had a spatial resolution of approximately 30 m and such topographical features were not captured in the DEM. Nonetheless, the runout extents were generally properly simulated.

For the three cases where LiDAR data were available, the results were compared to simulations using the lower-resolution DEM. For two of the studies, the results were very similar. For the third study, the LiDAR data better modelled the field observations (Figure 3). The avalanche path includes a ridge in the centre of it, which generally deflects flow to either side of it. The LiDAR data incorporated this ridge, but the lower-resolution DEM did not capture it due to its coarser resolution. Using high-resolution topography is therefore advantageous if the terrain is undulated, such as with prominent ridges and gullies that may affect flow. If the terrain is relatively smooth, using a lower-resolution DEM may suffice and has the advantage of decreased modelling time.

For cases that had measured debris thicknesses, the simulations were generally within a few metres of those observed. For simulations that were drastically different than observations, this often occurred where there was a sudden change in slope angle, such as a hockey-stick shaped path. Under such scenarios, once the front of the deposit stopped, remaining material accumulated directly behind it and sometimes simulated deposit thicknesses substantially higher than observed. In general, debris thicknesses were higher when entrainment was included in the simulation than without (e.g., Figure 2).

Velocities were not available for most of the cases. The modelled maximum velocities were typically between 30 and 60 m/s. These are within the range of maximum velocities listed in other studies (e.g., McClung and Schaerer, 2006; Sovilla et al. 2006).

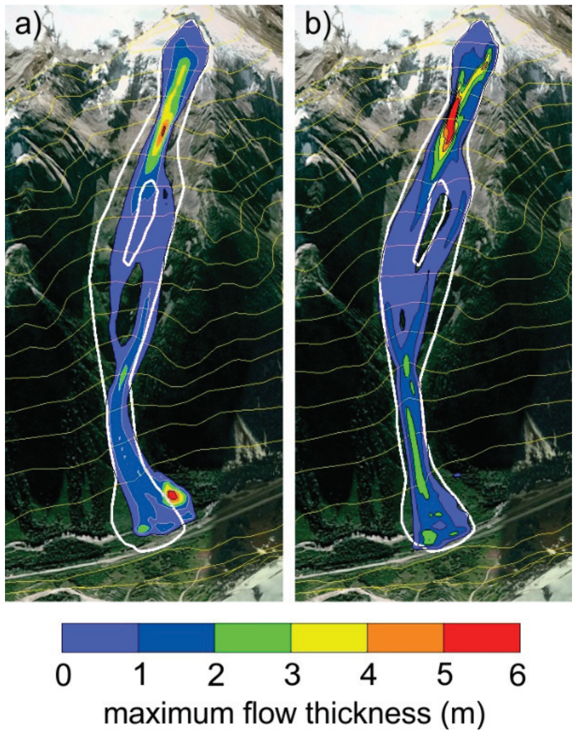

Figure 3. Simulation of a snow avalanche with Dan3D using a) the freely-available Aster2 DEM with 30 m resolution and b) LiDAR DEM with 5 m resolution. White outlines are observed flow boundaries. Thin yellow lines are 100 m elevation contours.

To evaluate Dan3D's ability to model velocity, the case study from NGI was simulated. The best parameters when entrainment was included were a friction coefficient of 0.2 and a turbulence coefficient of 3000. The simulated velocity profile matched the observed profile well, including almost identical maximum velocities of 43 m/s in the track. Without entrainment being modelled, the best parameter values were a friction coefficient of 0.15 and a turbulence coefficient of 3000. The velocity profile was comparable to the model with entrainment, but the deposit dimensions did not match observations as well as the model with entrainment. Our findings differ from Sovilla et al. (2006), who could not effectively use a Voellmy-based rheology to simulate velocity profiles with entrainment. However, we only evaluated one case study; assessing numerous other cases would be required to make a proper assessment. Nonetheless, we see the importance of including entrainment for modelling snow avalanches.

4. SUMMARY

Twenty-seven snow avalanche case studies were simulated with the Dan3D dynamic model. In general, Dan3D reproduced the bulk characteristics of the cases, such as runout and lateral extents, deposit thickness, and maximum flowing velocity.

In a few cases, these characteristics were not simulated properly, and often this was because of Dan3D's sensitivity to the input path topography. Where the lower-resolution DEM's were too coarse to include important topographical features, higher-resolution DEM's from LiDAR or photogrammetry would provide more realistic simulations.

Future work could focus on analyzing more cases with velocity profiles. Velocity data would allow for model parameters to be refined, so the variances of the distributions of the parameters for each mountain range would likely decrease.

Although calibrated parameters are included within this study for western Canada, site-specific calibration of Dan3D parameters is still required due to the relatively small dataset within this study and large area incorporated in the mountain ranges. Results from Dan3D should be used alongside other investigative techniques, such as vegetative surveys, historical records, statistical models, and other dynamic models. If used appropriately, Dan3D can be a useful tool to aid experienced professionals with hazard assessments for planning purposes.

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