INVESTIGATING DYNAMIC MODEL FRICTION PARAMETERS FOR LOW-VOLUME END-OF-SEASON AVALANCHES

Cam Campbell*, Eirik Sharp, and Alexis Tessier

Alpine Solutions, Canada

ABSTRACT: Operational avalanche risk management often relies on subjective assessments of potential avalanche runout extent to determine when the avalanche season has ended, and the seasonal avalanche risk management operations can finish. The potential avalanche runout extent depends on factors such as release volume as well as avalanche flow dynamics in the track and runout zones. Dynamic avalanche models are often used for estimating avalanche velocity and deposit volumes. These models have been calibrated for extreme avalanche events, which are useful for mapping and engineering purposes. However, estimating potential avalanche runout for shorter return periods could be valuable for operational avalanche risk management and could inform the end of avalanche season decision. While previous studies have focused on the sensitivity of dynamic avalanche model results on release volume, there are currently no numerical runout model parameters for calibrated for high-frequency (e.g., annual) avalanche events in western Canada. This study analyzes runout distance by release volume from 71 avalanche occurrence records from 1979 to 2022 for Path 51 on Highway 99 and investigates AVAL-1D dynamic model friction coefficients for low-volume end-of-season avalanche events using the occurrence data. The results can be used to help reduce the uncertainty associated with estimating potential runout extent for Path 51 and may inform friction parameter selection for numerical modelling of non-extreme avalanches on other paths.

KEYWORDS: Release volume; runout distance; model parameters; avalanche forecasting

1. INTRODUCTION

Determining the end of avalanche season is often a difficult decision avalanche forecasters face. The scenarios to consider when making this decision typically revolve around the potential avalanche runout extent given the amount and stratigraphy of snow in the starting zones (i.e., potential release volume) and the condition of the track. If there is still a significant amount of snow in the starting zone and the track is smoothed from previous avalanches, then the decision to maintain avalanche forecasting and control programs can be simple. Conversely, if there is relatively little snow in the starting zones and the track and upper runout zones are largely melted out, then the decision to end avalanche mitigation efforts is also often simpler.

It is the in-between scenarios that present the difficult decision. Perhaps there is relatively little snow in the starting zones, but the track is very smooth, or the track is starting to melt out, but there is still a significant amount of snow in the starting zones. These are the scenarios that we focus on with our research to help forecasters estimate the probability of an avalanche with a given release volume in a path with specific track conditions reaching a certain point.

This paper presents some initial investigations into the research question: Can dynamic model friction parameters be adjusted to explain variations in the relationship between release volume and runout distance for low-volume end-of-season avalanches. A summary of the analysis of occurrence records from an avalanche path in southwestern British Columbia, Canada is provided with the aim is to develop a set of dynamic friction coefficients to fit modelled simulations to observed results.

2. BACKGROUND

Dynamic numerical avalanche simulations, such as RAMMS (Rapid Mass Movement Simulation; Christen et al., 2010) and AVAL-1D (Christen et al., 2002), are commonly used in planning stage risk assessments to model extreme magnitudes for long return-period avalanches (CAA, 2016a). However, these models have had limited use in operational risk assessments. This limitation arises partly due to the sensitivity of model results to input variations, which have historically been calibrated against extreme avalanche events (Buser and Frutiger, 1980); the use of snow-free topography as a sliding surface (Bühler et al., 2011); and challenges in accurately initializing simulation because release volume, entrainment, and snow temperature all affect runout length (Valero et al., 2015).

Dynamic avalanche models are used to estimate avalanche characteristics such as velocity, deposit volume, and runout extent which are useful for understanding potential avalanches. While these models have typically been applied to and calibrated for extreme events (i.e., return periods greater than 30

* *Corresponding author address:*
Cam Campbell, Alpine Solutions
Vancouver, BC, Canada
tel: +1 778 868 5131
email: ccampbell@alpinesolutions.com
www.alpinesolutions.com

years), there is potential to use them for more frequent avalanches typically assessed in operational avalanche risk management programs.

Several studies (e.g. Dillon and Hammonds, 2021; Glaus et al., 2024; Stoffel et al., 2018; Valero et al., 2016) have explored the potential for RAMMS: Extended simulations, initialized with measured or modelled snowpack and weather data, to forecast avalanche runout distances. While these approaches are promising, they require further research into the appropriate model parametrization to accurately simulate non-extreme events before they can be broadly implemented as a predictive tool.

Modern avalanche dynamics models are typically based on the Voellmy friction law (Voellmy, 1955), which divides frictional resistance into two parts: a dynamic friction coefficient (μ) that scales with the normal stress, and a velocity-dependent turbulence coefficient (ξ) that accounts for viscous-turbulent drag. These coefficients are responsible for the behavior of the modelled avalanche flow, where μ dominates when the flow is close to stopping, ξ dominates when the flow is running quickly. In other words, μ dictates how far the avalanche runs, while ξ dictates how fast the avalanche travels.

In addition to flow velocity and liquid water content (e.g., dry versus wet flowing avalanches), these parameters are dependent on the shape of the terrain (e.g., uniform, channeled, gullied) as well as vegetation (e.g., forested, open).

Salm et al. (1990) adapted Voellmy's model to include active and passive pressure, which became known as the Voellmy-Salm model. There are several published values of ξ and μ for use with the Voellmy-Salm model (e.g., Schaerer, 1975 & 1981; Martinelli et al., 1980; Buser & Frutiger, 1980; Salm et al., 1990; Mears, 1992; Gubler, 1994). However, these values are typically based on observed runout distances of avalanches with ≥ 30-year return periods. Although, Gubler (1994) recommends μ between 0.20 and 0.30 for smaller avalanches with lower mean return periods and volumes < 10,000 m^3.

There are also several previous studies that have focused on the sensitivity of the Voellmy-Salm model and RAMMS to various input parameters (e.g., Borstad & McClung, 2009; Buhler et al., 2011; Heredia Guzman, 2021). These have found that the estimated runout distance is sensitive to initial release volume; however, few have focused on release volume inputs specifically for large avalanche paths with low-volume avalanches (i.e., < 10,000 m^3).

3. STUDY SITE – PATH 51

Avalanche Path 51 is located on Highway 99, approximately 150 km northeast of Vancouver in the Coast Mountains of southwestern British Columbia, Canada (Figure 1). The starting zone ranges in elevation from approximately 1700 m to 2300 m and has a primarily northwestern aspect. The track is approximately 1100 m long and descends from approximately 1700 m to 1000 m with an average slope angle of 26°. It is highly channelized throughout its entire length, with an approximate width ranging from 20 m to 50 m. Avalanches run out onto Duffy Lake, with the highway intersecting the path at the top of the runout zone (Figure 2).

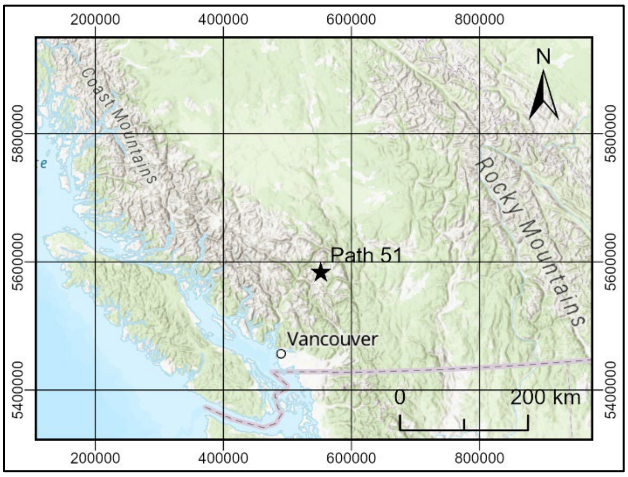

Figure 1: Path 51 is located approximately 150 km northeast of Vancouver in southwestern British Columbia, Canada (Projection: NAD83, UTM Zone 10N).

Figure 2: Photo of an explosive-triggered avalanche in Path 51 on May 14, 2012. The highway crosses the bottom of the photo, where most of the debris has accumulated (Source: MoTI).

This is the most active avalanche path along the stretch of Highway 99, known as the Duffey Lake Road. Avalanche risk for the highway is monitored and controlled by full-time Ministry of Transportation and Infrastructure (MoTI) avalanche forecasters with the aid of a GazEx system installed in Path 51 in 1992. In 43 years of occurrence records (i.e., 1979-2022), avalanches originating in Path 51 have reached the highway 119 times, averaging almost three times per year.

Since 1997, there have been five occurrences of naturally triggered avalanches reaching the highway when it was open to the public in the month of May. These surprise avalanches highlight the need for better tools to aid decisions associated with forecasting the end of avalanche season.

4. ANALYSIS OF OCCURRENCE RECORDS

In order to develop a decision aid to assist with determining when mitigation efforts are no longer needed, an analysis of release volume and runout distance was completed for Path 51. In the 43 years of record-keeping, over 1300 avalanche observations were made according to Canadian Avalanche Association guidelines (CAA, 2016b). These included estimates of slab width and depth and estimates of runout distance for over 200 slab avalanches. Observed avalanches were also classified as Dry, Moist, or Wet according to liquid water content classifications in CAA (2016b); however, these are poorly defined.

4.1 Dataset

For our analysis we filtered the data to only include avalanches that reached within +/- 150 m of the highway with slab widths between 50 m and 300 m and slab depths ≥ 50 cm. These thresholds were assumed to include a subset of the avalanche occurrences that have the most uncertainty when forecasting runout distance. This left us with 71 records for analysis: 21 Dry, 33 Moist, and 17 Wet avalanches. Seventeen of the 71 (24 %) avalanches analyzed occurred naturally, while 54 (76 %) were explosives-triggered.

In order to calculate release volume, a slab length was assumed based on proportions measured by McClung (2009). Specifically, a ratio of 1.2:1 (width:length) was used. The Dry flowing avalanches tended to have larger release volumes, with an average of 11,360 m^3, while Moist avalanches had an average release volume of 8387 m^3, and Wet avalanches had an average release volume of 7109 m^3.

Despite the larger release volume, a lower proportion of the Dry avalanches observed reached the highway. Of the 21 Dry avalanches analyzed, 11 (52 %) reached the highway, while 28 of the 33 (85 %) of the Moist avalanches and 14 of the 17 (82 %) of the Wet avalanches reached the highway. This is possibly due in part to 19 of the 21 (90 %) the Dry avalanches occur before the month of April, when the track has less snow and previous avalanches to smooth it out. While 23 of 33 (70 %) Moist avalanches and 12 of 17 (77 %) Wet avalanches occurred in April and May, when the track is more filled-in and smooth. This is supported by a general trend of increasing runout distance as the avalanche season progresses, regardless of avalanche type.

Figures 3, 4, and 5 are plots of release volume versus runout extent for Dry, Moist, and Wet avalanche observations, respectively. The runout distance is based on the distance from the highway, with 0 m representing the uphill edge of the highway, negative numbers representing the distance above the highway, and positive numbers representing the distance across and downslope of the highway.

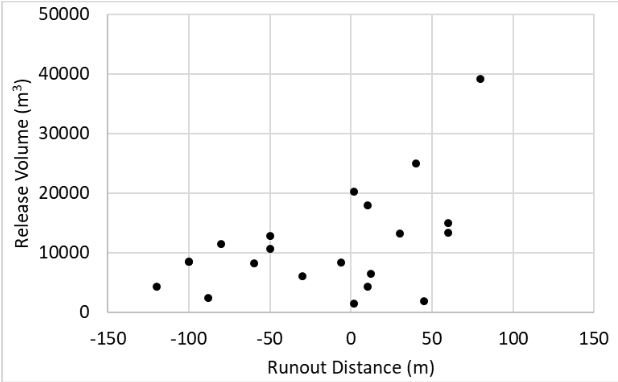

Figure 3: Scatterplot of release volume versus runout distance relative to the highway for Dry slab avalanches in Path 51 (N = 21).

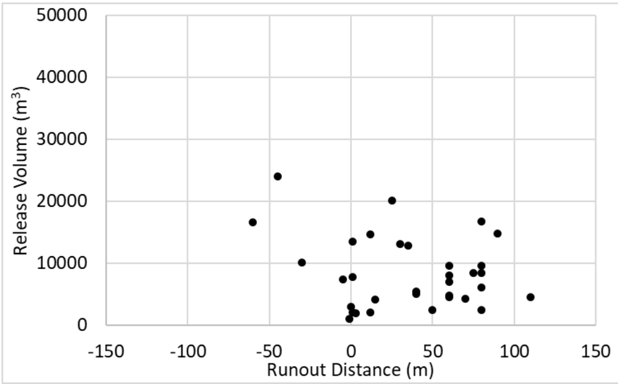

Figure 4: Scatterplot of release volume versus runout distance relative to the highway for Moist slab avalanches in Path 51 (N = 33).

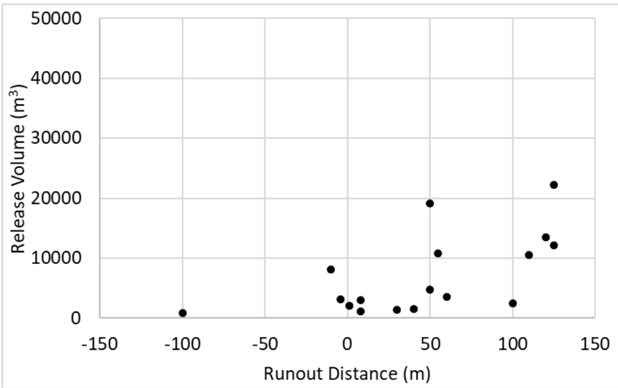

Figure 5: Scatterplot of release volume versus runout distance relative to the highway for Wet slab avalanches in Path 51 (N = 17).

As can be seen in Figures 3, 4, and 5, there is considerable variation in runout distance for a given release volume. While Dry (R^2 = 0.25) and Wet (R^2 = 0.37) avalanches have a statistically significant positive correlation between release volume and runout distance ($p < 0.05$), the correlation with Moist avalanches was not significant. This variation in runout distance for a given release volume is assumed to be largely due to variations in track conditions and associated μ.

4.2 Late Season Avalanches

During late season (often May), when forecasters are often faced with the question of whether there is sufficient snow in the staring zone to produce an avalanche that reaches the highway, track conditions can have distinct characteristics. The track can be completely snow-covered from top to bottom with a smooth icy snow surface, like a luge track, created by previous avalanches. Alternatively, the track can have rough bare ground to an elevation depending on the degree of melting, but rarely above the midpoint in May.

In order to quantify the variability in runout distance caused by these different track conditions, a similar analysis to that described above was used for the subset of avalanches that occurred in May. The data subset contained 28 records of explosives-triggered and naturally occurring slab avalanches, including the five natural avalanches that impacted the open highway. All of the avalanches were classified as either Moist or Wet (i.e., no dry avalanches), with all but three reaching the highway.

Figure 6 is a scatterplot of release volume versus runout distance for the combined dataset of Moist and Wet avalanches in May. The release volume ranged from 933 m^3 to 22,183 m^3 with an average of 7842 m^3. The five natural avalanches that impacted the open road had volumes ranging from 1600 m^3 to 13,500 m^3, with an average of 6331 m^3, which was characteristic of the data subset.

As can be seen in Figure 6, the May avalanches showed a statistically significant positive correlation between release volume and runout distance ($p < 0.05$). The 95% confidence intervals are assumed to represent typical track conditions associated with the two extreme cases where the track is either smoothed (upper bound) or melted out (lower bound). Also, of note, all avalanches with a release volume greater than 10,000 m^3 reached the highway (i.e., runout distance > 0 m).

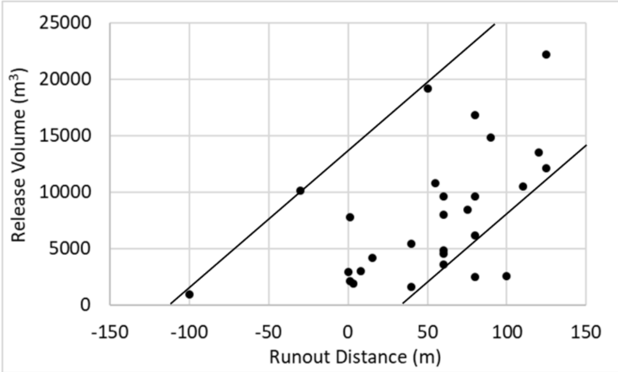

Figure 6: Scatterplot of release volume versus runout distance relative to the highway for Moist and Wet slab avalanches in Path 51 in May (N = 28). The 95% confidence intervals (black lines) are also shown.

5. NUMERICAL MODELLING

Due to a lack of sufficiently high-resolution digital terrain data, avalanche simulations using RAMMS were not possible. The AVAL-1D numerical avalanche dynamics model (Christen et al., 2002) was used instead to simulate dense avalanche flow in Path 51 for release volumes ranging from 2500 m^3 to 10,000 m^3. The AVAL-1D model is based on similar physical processes and uses similar parameterization to RAMMS; however, avalanche velocity is only resolved in one dimension.

Default friction parameters associated with unchanneled wet avalanches (i.e., μ = 0.310; ξ = 1200 m/s^2) were used for the starting zone, while μ was adjusted for the track and runout zone to fit the runout distance the observed extreme cases illustrated in Figure 6 (i.e., smoothed track and melted out). For the smoothed track scenario, a constant μ was used for the entire track. However, for the melted-out scenario, the track was bisected into an upper and lower portion with a separate μ for each section to represent varying degrees of melting (i.e., elevational extent). A constant ξ of 1200 m/s^2 was used for the entire track and runout zone for the purposes of this preliminary study.

The results of the numerical modelling are presented in Table 1 and Figure 7. For the smoothed track scenario, a μ of 0.100 was required to fit the estimated runout distance for the 2500 m^3 release volume to the observed runout distances. However, for the larger release volumes, simulations showed that a constant μ of 0.170 can be used to estimate runout distance for a given release volume. For the melted-out scenario, increasing values of μ for both the upper and lower track were required to fit the modelled runout distance with the observed data. Values of μ ranged from 0.100 to 0.425 for the upper track, and 0.300 to 0.430 for the lower track. These values seem reasonable when compared to published values for extreme avalanche events.

Table 1: AVAL-1D simulation parameters and results for smoothed track and melted out scenarios described in Section 4.2.

Track Type	Release Volume (m^3)	μ Upper Track	μ Lower Track	Runout Distance (m)
Smoothed Track	2500	0.100		42
	5000	0.170		73
	7500	0.170		94
	10,000	0.170		104
Melted Out	2500	0.100	0.300	-81
	5000	0.270	0.400	-71
	7500	0.390	0.420	-50
	10,000	0.425	0.430	-30

Figure 7 is a plot of release volume versus estimated runout distance values listed in Table 1. A linear regression line is fitted to the points to illustrate the 95% confidence limits for all possible runout scenarios for a given release volume. These scenarios represent varying degrees of smoothed and melted out track conditions.

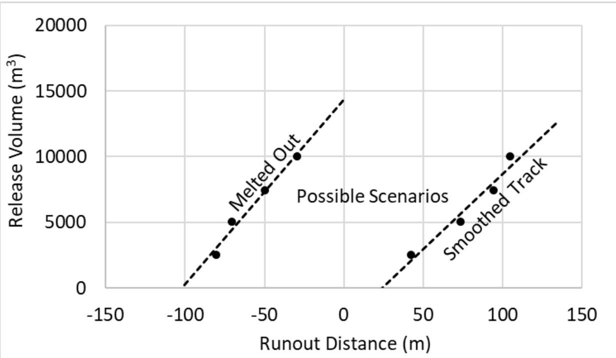

Figure 7: Release volume versus estimated runout distance relative to the highway for smoothed track and melted out scenarios listed in Table 1. Possible runout scenarios associated with varying degrees of melting would fall between the two extreme scenarios shown (i.e., with 95% confidence).

6. SUMMARY AND NEXT STEPS

This paper presents initial investigations into dynamic model friction parameters for low-volume end-of-season avalanche events in an avalanche path in Western Canada. The goal of these investigations is to develop a tool to assist with determining when mitigation efforts are no longer needed for an avalanche path at the end of avalanche season. The results show that end-of-season runout extent is dependent on release volume and track conditions, which can vary from completely snow-covered with a smooth icy snow surface (i.e., like a luge track), to melted out conditions with rough bare ground. Dynamic friction coefficients (μ) associated with these different track conditions were determined by fitting AVAL-1D simulated runout distances to observed avalanches.

Overall, we are cautious as to how far to extrapolate the friction parameter results from one model (i.e., AVAL-1D) for one path to other regions and to other models. Further research is expected to focus on other avalanche paths in different snow climates and use the RAMMS model to further refine parameterization for these low-volume high-frequency end-of-season avalanches. In addition, we plan to investigate the influence of ξ on estimated results.

We also plan to make in-situ slab volume measurements using drone-based LiDAR surveys before and after an avalanche. This is expected to result in better release volume estimates that can be used with detailed observations of the track conditions and runout extent to improve the accuracy of the observation dataset. Ultimately, we hope the results of this analysis can help inform further studies of dynamics associated with low-volume avalanches at the end of avalanche season.

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