SNOW AVALANCHE PENETRATION INTO MATURE FOREST

by

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Abstract

Clear cut logging in the mountainous terrain in British Columbia, Canada, is creating new snow avalanche start zones. These areas are capable of producing avalanches sufficient in size that they can penetrate into and destroy mature forest cover. The presence of these logging cut-blocks can augment the destructive potential of previously existing avalanche paths as well as create new avalanche start zones. Forest penetrating avalanches can pose a significant risk to down-slope structures and resources.

In this thesis, the first database containing information on penetration distances and lateral spread for avalanches that penetrate forest cover is developed. The study area for this research spans the Southern Coast and Columbia Mountains of British Columbia, Canada.

The analysis is focused on terrain characteristics that are related to forest penetration and the resultant destruction of mature standing forest. Physical terrain and vegetation characteristics in the avalanche starting zone, track, and runout zone of 45 forest penetrating avalanches are described, measured, and parameterized. The results provide predictive tools to assess probable avalanche runout distances, and the lateral spread of potential avalanche paths that contain forest in the track or runout zone.

KEY WORDS: snow avalanche, timber harvest, forest damage, penetration, clear-cut, runout, spread.

TABLE OF CONTENTS

List of Tables

List of Figures

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Chapter 1: Introduction

1.1 Introduction

Snow avalanche danger in the mountainous terrain of British Columbia, Canada, is a significant risk concern for managers of natural and human environments. Among other things, snow avalanches can pose a danger to highways, urban centres, hydro lines, long distance pipelines, animal habitat and forest resources. Avalanches can develop on virtually any slope steeper than approximately 25° (McClung and Schaerer, 1993), given that other conditions are also conducive to avalanche formation. In British Columbia, timber harvesting is a staple to the economy. Timber resources have been extensively used and the effects of logging are evident deep into B.C.'s mountainous backcountry. Many of British Columbia's backcountry valleys have been logged to the point where suitable harvest timber is not readily available at non-steep, low elevations. A consequence of this intensive harvesting is that timber harvesting companies have been forced to begin logging at higher elevations than was previously necessary. Logging of forest resources at high elevations in British Columbia generally results in the creation of large tracts of exposed, unstable land in very steep terrain that experience deep snow accumulation in winter. Removing vegetation from steep slopes can result in decreased winter snowpack stability. Thus, the high snow supply and steep slopes at higher elevations culminate in an increased danger for the creation of avalanche prone slopes when deforested. Down-slope human and natural resources are put at increased risk when avalanche terrain is created high on mountain slopes.

An environment-altering activity, such as timber harvesting, conducted in even slightly mountainous terrain should be completed with attention to the potential for the creation of dangerous avalanche terrain. Research into the dynamics of avalanche behaviour has therefore

become an increased priority for various public and private sectors during the last decade. In Canada, the industries concerned include ski area operators, helicopter skiing operations, highway management, and forestry (McClung and Schaerer, 1993).

In areas of concentrated human use such as the Coquihalla Highway in B.C., mitigation of avalanche danger is a serious issue. At great expense, retaining structures, snow sheds and active winter bombing are methods employed to protect the highway from avalanche danger. Logging adjacent to the Coquihalla Highway has long been a concern for the Ministry of Highways, B.C., due to the risk of large avalanches punching through the protective leave strips of forest running parallel to the highway (Weir, 2002).

In areas of lower human use such as B.C.'s extensive backcountry, the concern is not as great since the human density is less and so the risk to human life is greatly reduced. For economic reasons, the protection of future resources, and general environmental stewardship, these lesser used areas should not be ignored. Large avalanches in lower use areas can still have a significant impact on human activity, structures, natural processes, and forest resources. In newly created avalanche terrain in and around logging cut-blocks, trees, rock, and soil can be entrained into avalanches, augmenting their destructive power and ultimately resulting in debris deposits accumulating in valley bottoms. Often, the debris contains only snow and ice which is usually quickly undercut and melted once deposited in creek channels. In B.C., large areas of forest are destroyed every year by destructive snow avalanches running through and out of logging cut-blocks. In some cases where avalanche deposits contain entrained soil, rock, or tree materials, damming of creeks may persist and impede creek flows. When these dams are eventually breached the flow can be transformed from normal discharge into dangerous flood waters, putting downstream resources in danger of being flooded or destroyed. It is important to

be able to predict the distances that avalanches may travel through protective leave strips so the danger to features below these leave strips can be assessed.

In Canada, snow avalanches have been of great concern to the ski industry, and others such as the Canadian Pacific Railway since the late 1800s. Significant research began in the 1950s (Dennis and Geldsetzer, 1996); however, until the mid 1990s there had been virtually no avalanche research completed with a focus on logging practices. In Europe, the density of human settlements in mountainous areas is greater than in Canada; therefore, avalanche risk has been a more prominent concern for European mountain communities for centuries longer than in British Columbia. Now, as human settlements and winter recreation activities expand deeper into the backcountry areas of British Columbia and logging extends further into the alpine, the concern for the creation of potential forest penetrating avalanche terrain becomes increasingly important.

1.2 The Forest Penetration Problem

Forests are natural systems and are not human engineered to withstand the impact forces from avalanches descending out of logging clear-cuts. Until now no data have been collected to verify or prove that forests could be used in order to protect down-slope resources from avalanches running out of clear-cuts. It is, however, common practice for consultants to assess lower risk if a forest buffer exists between potential avalanche terrain and a down-slope resource or structure (Bay, personal communication, 2005). In fact, forest leave strips are retained by logging companies in order to protect down-slope features. It is assumed that the leave strips can prevent avalanches from descending out of cut-blocks. These are potentially dangerous assumptions and a quantitative method is needed to evaluate the potential for avalanches to penetrate through forest cover and put down-slope resources at risk.

1.3 Scope and Intent of the Research

The research presented here is the third component of a research initiative undertaken by the Avalanche Research Group (ARG) at the University of British Columbia. Through investigation of the interaction between timber harvested areas and avalanche activity the ARG has established a number of important recommendations and guidelines for safe harvesting practices in British Columbia. Since 1999, the ARG has been developing a comprehensive database containing information on avalanche occurrences in Southern British Columbia. The database contains data on quantified, parameterized, physical terrain variables, and has been used to establish relationships between physical terrain characteristics and avalanche–forest interaction. Until 2002 there were no guidelines that defined decision criteria for safely siting logging cut-blocks in terms of potential avalanche danger other than avoiding steep terrain (Stitzinger, 2001). Such guidelines were developed by the ARG in Stitzinger (2001) to address this problem. Modelling avalanche activity in forested terrain is necessary to provide decision support systems and guidelines for the timber harvesting industry in British Columbia.

This research contains statistically modelled terrain characteristics correlated with areal measurements of forest destruction. The ultimate goal is to develop guidelines to reduce the probability of creating destructive avalanche terrain through logging, to predict forest penetration distances, and to assess the probability of avalanches penetrating into mature forest cover.

In a general sense the overall questions addressed are: What are the appropriate, quantifiable, physical terrain and vegetation variables that can be measured and applied in a field situation and are useful for delineating logging cut-blocks to avoid or mitigate the subsequent destruction of forest by large avalanches? Which physical terrain characteristics are most highly associated with avalanche penetration into mature forest cover? Which terrain features can most effectively be used to predict the potential for avalanches to penetrate forest?

A goal of this research is to develop a model or models that will enable practitioners to assess the probability for cut-blocks to produce forest penetrating avalanches and to facilitate harvesting recommendations for safe cutting practices. The focus is on the identification of appropriate decision criteria based on measurable physical field parameters. To date, the most important variables correlated with the initiation of future destructive avalanches are thought to be slope angle, snow supply, tree type, tree density, tree height, and slope aspect (Stitzinger, 2001). In the research presented here, the analysis is taken further to show how other variables such as slope shape, distance to forest penetration point, and possibly cut-block design may be used to reduce the probability of forest penetrating avalanches occurring. For pre-existing cut-blocks, tools to predict the potential runout distances are presented.

1.4 Background

1.4.1 Risk vs. Hazard

The terms risk and hazard have specific and different meanings in different industry sectors and so it is necessary to define the terms in their context for the research presented here. In this thesis, avalanches which have penetrated forest cover are examined; the two sectors of interest here are the forestry industry and the broad umbrella of the avalanche forecasting community. To avalanche professionals in British Columbia, hazard means "the potential to inflict death, injury, or loss to people or to the environment" (Weir, 2002). A forester defines hazard as the likelihood, or probability of an event (MoF, 2001). In the context of this research, any reference to hazard comes from an avalanche professional's perspective.

Avalanche risk is defined as the probability or chance of death or losses and is determined by the combination of frequency, damage, and exposure (Canadian Avalanche Association, 2002). Foresters are required to have avalanche risk assessments conducted to

address: "Long-term (or spatial) problems, where the concern relates to prediction of future avalanche susceptibility (e.g. where an avalanche start zone might be created by forest harvesting or fire, at some time in the future, on previously unaffected terrain)" and "short-term (or temporal) problems, where the concern relates with real time avalanche assessment and forecasting in recognized avalanche terrain. Public and worker safety and resource protection are key issues." (Weir, 2002).

In research presented here, I examine forest cover that has been destroyed by avalanches descending out of relatively newly created avalanche terrain (logging cut-blocks). Implicitly, there is a minimum magnitude threshold (the smallest avalanche category according to the Canadian Avalanche Size Classification with the ability to break trees is a size 3) and frequency measures are just becoming relevant since many of the cut-blocks in question are younger than 10 years and have not necessarily produced more than one avalanche. Any reference to risk, unless otherwise stated, refers to a forester's understanding of risk where the concern relates to the creation of new avalanche terrain, and the protection of down-slope human and natural resources.

1.4.2 Avalanche Types

There are essentially two types of avalanches: loose snow avalanches and slab avalanches (McClung and Schaerer, 1993).

Slab avalanches are normally the more dangerous and damaging of the two. Slab avalanches can be further broken into two subcategories: dry and wet slab avalanches. Dry slab avalanches move quickly and can produce a powder blast which in extreme cases can damage branches or tree bark. It is primarily the dense body of the avalanche which is of greatest concern to forest resources. Slab avalanche conditions can build over large spatial areas (metres

to hundreds of metres) and are characterized by well-defined fracture lines at the crown with well-defined flanks. The resultant form of a slab avalanche is approximately rectangular.

Wet slab avalanches can also be destructive; they occur when the water content of the snow is relatively high. The water content of a snowpack can be increased through a rain event or during the spring melt. The three mechanisms for a wet snow slide release are 1) the increased mass of the snow from rain loading causes failure in the weak layer, 2) the weak layer strength is altered by the presence of water and 3) water may lubricate the sliding surface (McClung and Schaerer, 1993). Wet slab avalanches tend to be slower moving than dry slab avalanches but the increased density of a wet slab can result in an equal or greater destructive power.

Loose snow or sluffs initiate at a point and generally have a triangular (widening down-slope) shape as down-slope snow becomes entrained in the flow (McClung and Schaerer, 1993). A lack of local snow cohesion at or near the surface of the snowpack can cause the initial failure; slide volume is increased as more snow is entrained during the descent. Sluffs do not contain as much energy or mass and therefore do not have the potential to cause as much destruction as slab avalanches. Sluffs are typically too small to cause any significant damage to forest cover; therefore, the avalanche types addressed in this thesis are large dry slab or wet avalanches.

1.4.3 Avalanche Size

Since forest destroying avalanches are the focus in this research, there is an inherent minimum avalanche size that can be considered. The Canadian Avalanche Size Classification scheme is used here to estimate the size of each event. Table 1.1 gives a breakdown of how the classification scheme determines the size of the avalanches.

Table 1.1: Canadian Avalanche Size Classification Scheme (McClung and Mears, 1991).

Canadian Snow Avalanche Size Classification System				
Size	**Description**	**Typical Mass**	**Typical Path Length**	**Typical Impact Pressure**
1	Relatively harmless to people	<10 t	10 m	1 kPa
2	Could bury, injure or kill a person	10^2 t	100 m	10 kPa
3	Could bury a car, destroy a small building, or break a few trees	10^3 t	1000 m	100 kPa
4	Could destroy a railway car, large truck, several buildings, or a forest with an area up to 4 hectares	10^4 t	2000 m	500 kPa
5	Largest snow avalanches known; could destroy a village or a forest of 40 hectares	10^5 t	3000 m	1000 kPa

Size two avalanches can damage forest by breaking branches or scarring bark. However, by definition, the smallest sized avalanche containing enough energy to break trees is size three. When all factors are considered and given varying researchers' estimation of size, and given that some examples have damaged very little timber, the mean avalanche size in the data used here is 3.5 with a minimum of 2.5. According to the Canadian Standards, frequent size 2 avalanches can produce moderate risk but are not likely to penetrate forest cover.

1.4.4 Forests in Mountainous Avalanche Terrain

Forest cover on steep slopes increases slope stability with respect to snow avalanches in a number of ways. Physical snow retention properties of standing forest, tree stumps, canopy drip, and modification of the radiation regime in and under a forest cover can all contribute to stabilizing the snowpack.

1.4.4.1 Protection Forests

In Europe, research into protection forests has been conducted for many years. Only minimal success has been realized through the use and engineering of protective forests and retaining structures to protect settlements from avalanches in motion (Montagne et al., 1984), and to prevent avalanche initiation (Ott, 1978). Only recently, primarily in British Columbia, has the interaction between forests and avalanches become of interest to planners and industry. In British Columbia in the mid 1990s there was a rise in the number of documented avalanche/forest interactions as a result of clear cutting on mountain slopes (Hein, 1995, Stellar Consulting Services, 1996a, Stellar Consulting Services 1996b). The increase in documentation has fostered a greater general interest and inspired intensive research into this phenomenon.

It is known that a high forest cover density or the use of retaining structures in starting zones can be effective in preventing avalanche initiation. The utility and protective function of leave strips below forest cut-blocks has not yet been assessed. The utility of forest leave strips used to protect down-slope resources from avalanches in motion is not well understood. Relatively large trees (height and diameter), and high tree density increase the 'stopping power' of a forest to avalanches (Brang, 2001), but the relationship with other physical terrain variables is not understood. If, in a deforested area, an avalanche is triggered, impact forces on the down-slope forest can be great if the avalanche has even 100 m distance to gain momentum. Impact forces depend on snow density and impact velocity (McClung and Schaerer, 1993). Impact pressures great enough to damage and penetrate forest lie approximately between 30 and 100 kPa; 30 kPa is enough to destroy wood frame structures, and 100 kPa is the estimated force needed to uproot a mature spruce (McClung and Schaerer, 1993). It is possible that smaller avalanches, possibly as small as a size 2 avalanche according to the Canadian Avalanche Size

Classification Scheme, could gain enough force to penetrate through forest cover if funnelled into a gully. It has been suggested that trees as large as 30 cm in diameter can be broken by an avalanche running as little as 30 m down-slope (Gubler and Rychetnik, 1990).

Planting forests may be important for avalanche control in mountainous regions to protect settlements and roadways by stabilizing the snowpack (Frey, 1992). However, different types of forest have different abilities to protect. According to Brang (2001), the protective nature of a forest stand depends on the stand structure (density, tree height, and tree diameter at breast height). In British Columbia, relatively thin mountain soil cover and shallow root penetration of the forest cover may not provide adequate forest stability to prevent avalanches from penetrating into and breaking or overturning forest cover. Cut-blocks are often designed with a protective leave strip of forest between the cut-block and any built structure or important natural down-slope feature. Leave strip techniques may not be adequate in many situations. Retaining forest below a potential avalanche starting zone may not provide sufficient retarding power to stop an avalanche.

The presence of forest cover may actually augment the potential for down-slope damage if an avalanche succeeds in snapping or overturning any trees at the bottom boundary of a cut-block. Large trees can become entrained in the flow of an avalanche, increasing the overall density of the avalanche and increasing the height of potential damage as trees are carried down-slope on end. Trees entrained in the flow can extend laterally from the body of the slide, increasing the width and creating a battering ram effect whereby the entrained trees actually widen the swath of damage compared to that which the snow alone would damage. Trees augmenting the destructive potential of avalanches indicate that protection forests are not a simple, straight-forward tool to protect down-slope resources.

The B.C. Ministry of Highways uses alpha angle analysis as a rough guide to determine whether cut-blocks along roads could produce avalanches that impact the road. The alpha angle (α) is the angle determined by sighting from the maximum runout position to the top of the start zone. A 25° α angle is the boundary between whether a slope must undergo further assessment or no further assessment is required. If the top of a cut-block is situated where the angle from the road to the top of the start zone is less than 25° the position is considered relatively safe from avalanche danger and is not likely to require further assessment. In practice, if the angle from a given position to the top of the start zone is close to 25° and forest cover exists in the track and/or runout zones (anywhere between the given position and the start zone) the position may be considered safer than it otherwise would were forest cover not present. This may not be a safe practice and it has been made clear that consideration of other site specific terrain features should be as important as relying on α angle guidelines (Bay, pers. comm., 2005). For example, if the terrain is gullied rather than open, the likelihood for avalanches to break and penetrate through protective forest is probably higher. There are numerous examples of large avalanches running to a runout much shallower than 25°, including at least one case that penetrated through forest cover. These examples will be examined, and appropriate techniques to evaluate the 'safety value' of forest will be presented in the next 2 chapters.

1.4.4.2 Stump Retention and Tree Density

Various researchers suggest that retaining relatively dense forest after timber harvesting can help to avert avalanche initiation (McClung and Schaerer, 1993, Stellar Consulting Services, 1996a). Opinions vary on the relative contribution of the static, physical presence of tree stems. Trees physically hold the snowpack in place, resulting in slide release being less likely in a forested area than in open areas. However, there are other influences produced by forest cover which may be as effective in increasing snow stability. Some suggest that the physical presence

of forest plays a minor role in preventing avalanches when compared to other influences exerted by the forest such as the alteration of radiation regimes and creation of canopy drip (Weir, 2002). Others believe that the static presence of forest is the primary mechanism in preventing avalanche initiation (McClung, pers. comm., 2005). Early estimates projected that a tree density of 500 to 1000 stems/ha would be sufficient to mitigate the propensity for avalanches to start (de Quervain, 1978). A density of about 700 stems/ha can provide 'good' tree skiing (Welch, pers. comm.); and it would seem that a multi-use approach (backcountry/heliskiing and selective logging) could be an appropriate method to prevent the creation of new avalanche starting zones. It is currently thought that maintaining a density of 1000 trees/ha or greater (Stitzinger, 2001), if the diameter at breast height is 12-15 cm (Weir, 2002), may be sufficient to prevent avalanches from starting. Johnson et al. (1985) suggest that trees with a diameter greater than 10 cm will be uprooted or broken when struck by an avalanche with significant force.

Post harvest stump retention can reduce the potential for avalanche initiation if the tops of the stumps project above the surface of weak layers within the snowpack. Stumps of sufficient height can prevent the development of uninterrupted pervasive weak layers on a large spatial scale. There are some problems associated with this approach that prevent stump retention from being a suitable solution. According to Weir (2002), "ten year old trees 1.5 m to 2 m in height offer little protection for a snowpack 1.25 m deep". In much of British Columbia, effective stump retention would require stump heights approximately 2-3 m in order for stumps to extend above weak layers within the snowpack and offer protection against avalanches in motion. Tall stumps on a slope are aesthetically undesirable. The roots dissolve in approximately seven years leaving a field of stumps that provides no resistance or protection to avalanches in motion. In theory, if stumps of this height are left on a slope, harvesting, planting and multi-use operations are compromised. Drag chain operations are hindered by freshly felled timber becoming wedged

between stumps, and heavy equipment can be severely damaged as high stumps can scrape and dent the undercarriage of vehicles. Leaving large stumps in cut-blocks also creates an undesirable recreational hazard for backcountry users, destroying ski terrain and causing hazards for snowmobilers.

In British Columbia it is often impossible to selectively log and retain a stem density of 1000 stems/ha due to the relatively low-density of old growth forests. Through replanting, silviculture practices strive to regenerate forests by planting densities that range between approximately 1400 and 2000 stems/ha (Tsuga Forestry, pers. comm., 1999). Silviculture in most of British Columbia strives to achieve an initial density of about 1300 to 1600 stems per hectare to promote maximum tree growth and yield (Pollack, accessed Oct. 2003). The regeneration success rate is expected to be in the range of 60% to 70% resulting in a mature forest density just barely equalling or less than 1000 stems/ha. For this reason, it may not be possible to use selective cutting as mitigation to maintain a density of 1000 trees/ha. However, it may be possible to establish relationships between other controllable terrain variables and damage areas that could lead to 'safer' harvesting practices with respect to avalanches.

1.4.4.3 Canopy Drip

A forest canopy increases the stability of a snowpack by producing canopy drip. Canopy drip occurs when snow and melt-water intermittently drop from tree branches to the snowpack below. Snow and water dropping from tree branches penetrate and percolate into the snow, sporadically interrupting pervasive weak layers and reducing the likelihood of avalanche release (Bründl, 1999). When a slope is deforested there is no mechanism for canopy drip to occur and the stabilizing effects are removed.

1.4.4.4 Radiation

Snowpack stabilization can occur through short-wave radiation interception by forest cover. When incident solar radiation is prevented from directly striking the snow surface by tree branches, the temperature at the snow surface does not change (rise) as rapidly during the day as it would were there a lack of forest cover. A lower rate of temperature change at the snow surface can reduce the temperature gradient within the snowpack, thus generating a lower potential for near surface faceted crystal development than if forest cover were absent. If forest cover is absent, direct short-wave radiation input raises the temperature of a snowpack which can result in avalanche release. The result is an increased rate of snow crystal metamorphism and a softening of the snowpack during daylight hours in deforested areas. Solar radiation has a differential heating effect according to slope aspect, and slope angle. In British Columbia, southern aspect slopes are the most influenced by solar radiation.

The near surface long-wave radiation regime is also altered by the presence of forest cover. Surface hoar can grow if two primary conditions are met. Water vapour must be available in the air directly above a dry snow surface (high relative humidity, >70%), and a temperature inversion must be present in the 1 m layer of motionless air above the snow surface (McClung and Schaerer, 1993). Longwave radiation loss (radiative cooling) at the snow surface at night can create the temperature inversion necessary for the growth of surface hoar. A forest canopy alters the longwave radiation regime with respect to the influence realized on the snowpack. The trees themselves emit longwave radiation, keeping the surface of the snowpack warmer than if forest were absent, and reducing the potential for cooling that is necessary for surface hoar growth. The presence of a forest cover means the radiative cooling that facilitates hoar crystal growth is reduced, even under clear night-time skies.

1.4.4.5 Wind Regime

Physical characteristics of mountain slopes are altered when a clear-cut is created and environments conducive to avalanche initiation can be created through these changes. One component that is altered when a clear-cut is created is the wind flow pattern in and around the cut-block, specifically around treelines and ridgelines. A change in the wind pattern alters the way snow is deposited on a slope and hence can affect differential loading on a slope. Wind loading can create conditions favourable for avalanche release. A five part wind index, described in Chapter 2 (Schaerer, 1977), is used to describe the wind regime according to the physical features of the slope, and classifies the type of loading a slope may experience. Figure 1.1 shows how the ridgelines and presence of forest cover can alter the snow deposition regime.

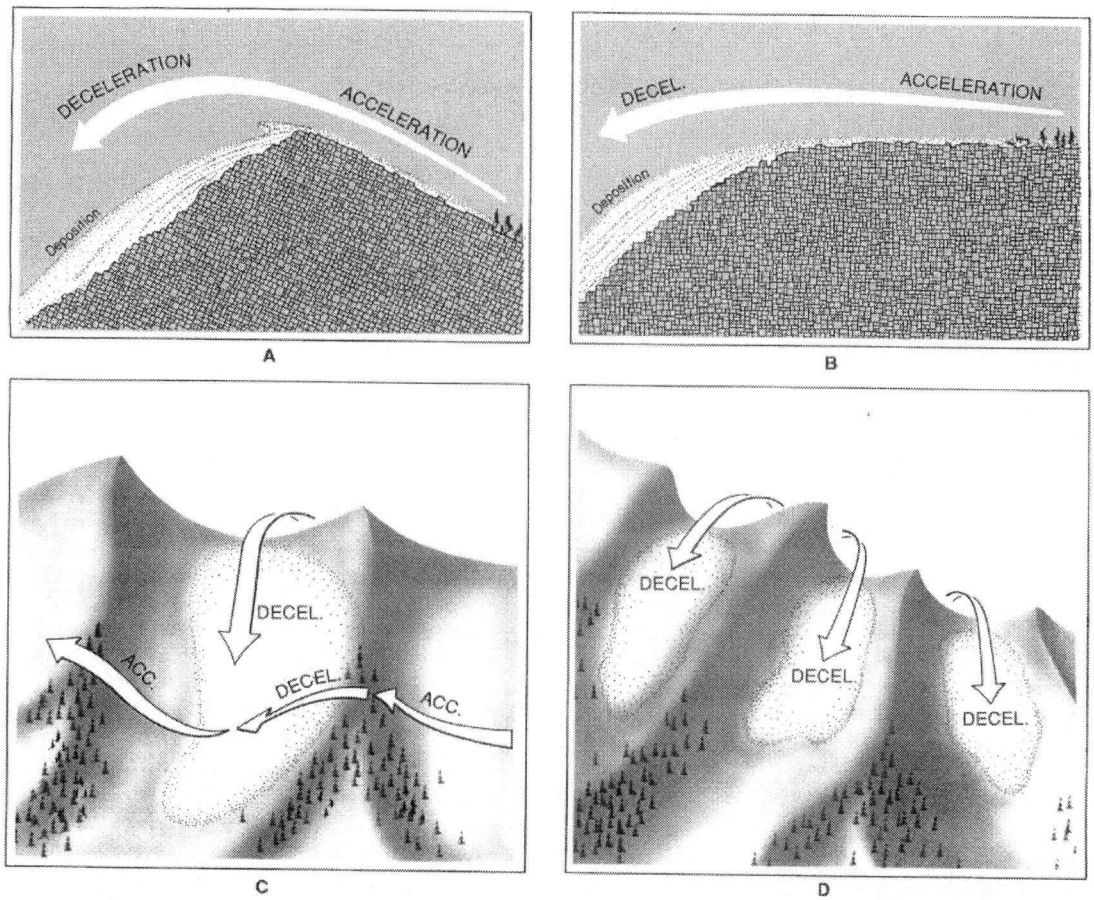


Figure 1.1: Diagram of various wind regimes and how snow deposition is influenced. Reproduced with permission from McClung and Schaerer, 1993.

Deposition tends to occur in areas of decelerating wind speed in bowl features on slopes. The cutting of forest creates these areas where snow is preferentially deposited, resulting in potential new avalanche start zones. The bowls in the diagram are represented and quantified in the field by the cross and down-slope shapes described in Chapter 2. Cross slope and down-slope shape are two variables which can be correlated to the penetration potential of avalanches.

1.4.5 Avalanche Terrain Classification

A classification scheme has been developed by the ARG to classify avalanches occurring in and around logging cut-blocks into three types: Type I, Type II, and Type III (McClung, 2001). The definition of each type follows below.

Type I (TI)

TI avalanches are those that initiate within clear-cuts and terminate within or below the cut-block.

Type II (TII)

TII avalanches are those that initiate above cut-blocks, terminating within or below the cut-block.

Type III (TIII)

A subset of TI and TII avalanches or other avalanches, TIII avalanche paths are those that initiate within or above cut-blocks and impact or penetrate into and destroy forest cover.

Forest cover is defined as a forest stand that is 5 m or greater in height; a full definition and rationale for the definition is presented in Chapter 2. The most important physical terrain parameters involved in avalanche initiation in logged terrain are thought to be surface roughness,

starting zone elevation (a proxy for snow supply), starting zone slope angle, slope aspect, wind loading, starting zone vegetation cover, cross slope curvature, and down-slope curvature (McClung, 2001). In spite of what is known about avalanches, the dynamics of avalanche/forest interaction are not well understood. Most research and forecast techniques for assessing the potential for avalanche release utilize antecedent snowpack and meteorological conditions. However, there have been no (known) modelling attempts that describe or quantitatively predict the potential for forest penetration based solely on physical characteristics of timber harvested terrain. To model forest damage, a number of parameters in addition to the ones described above must be identified and measured including: start zone length, diameter at breast height of penetrated forest, distance (horizontal and down-slope) to forest cover, vertical fall to forest penetration, distance (horizontal and down-slope) of forest penetration, vertical fall of forest penetration, forest damage width and area, and forest density at the point of forest penetration.

1.4.6 Modelling Approaches

There is a growing need in Canada to understand the dynamics of how avalanches interact with forested terrain, and most importantly, to ascertain the determinant variables leading to possible forest penetration and damage. These interactions must be examined in the field and quantified before any mathematical modelling can successfully be attempted.

In this research, a GIS is used in combination with field verification to digitally model avalanche paths that have interacted with timber harvested terrain. Destruction of forest is documented and delineated in order to identify and quantify the additional variables necessary to produce robust statistical models of forest damage.

The Swiss Federal Institute for Snow and Avalanche Research (SLF) has developed a number of avalanche dynamics models. These models are visually pleasing, but, they require inputs that must be estimated and currently cannot account for the retarding effects of forest

cover. In Canada, the ARG's statistical/probability risk based modelling is a more robust approach since the inputs can be derived from terrain alone and are not reliant on snow or meteorological conditions.

Probability modelling used in this work is based upon avalanche runout ratios. Runout ratios are calculated using the parameters presented in Figure 1.2 and described in equation 1.1.

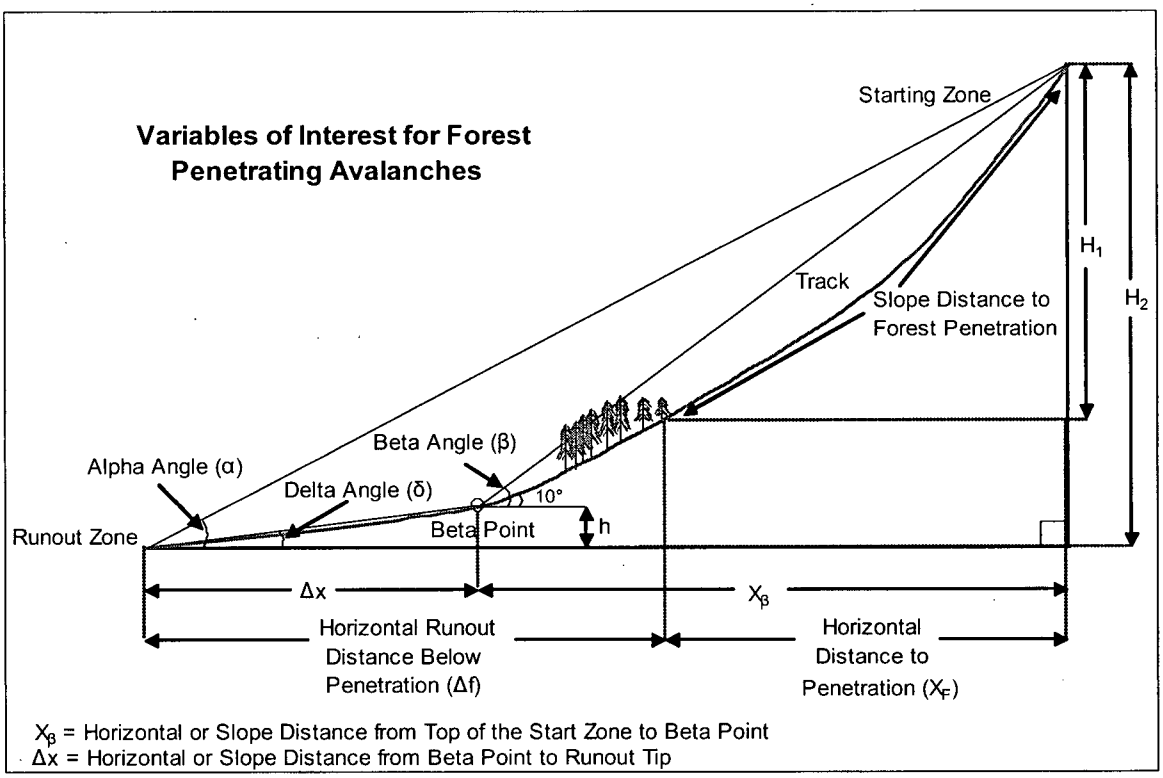


Figure 1.2 General schematic of a slope profile and relevant TIII variables.

In the slope profile diagram, classic runout ratio analysis employs the values represented by Δx and X_β. The runout ratio is a dimensionless measurement of avalanche runout distance (McClung and Mears, 1991). The variable X_β is the horizontal or slope distance from the top of the start zone to a reference position called the β point, and Δx is the horizontal or slope distance from the β point to the bottom of the runout zone. The β point is defined by the slope angle (Lied and Bakkenhøi, 1980) and in this research a 10° β point is used. The β point here is the

point on the slope which first becomes 10° descending from the top of the start zone. The β angle is defined by dividing Δx by X_β. If an avalanche terminates upslope of the defined β point, Δx is assigned a negative value, resulting in negative runout ratio values for avalanches that stop above the β point.

Another definition of the runout ratio is:

$$\Delta x/X_\beta = (\tan \beta - \tan \alpha)/(\tan \alpha - \tan \delta) \qquad 1.1$$

where $\Delta x/X_\beta$ is the runout ratio, β is the beta angle (sighted from the 10° point to the top of the start zone), α is the alpha angle (sighted from the bottom of the runout zone to the top of the start zone), and δ is the angle sighted from the maximum runout position to the β point.

For the probability analysis, the runout ratios for a particular mountain range or group of avalanche paths which contain similar characteristics are taken and fit to a probabilistic distribution. The probability that an avalanche will reach a given point on a slope can be calculated according to what has occurred on similar slopes.

1.5 Case Study Examples

Here I present examples of the destructive potential of avalanches. The examples examined are events which occurred at Nagle Creek, North Blue River, Haylmore Creek, and Gowan Creek, British Columbia. Figure 1.3 below shows the location of the four case study examples discussed.

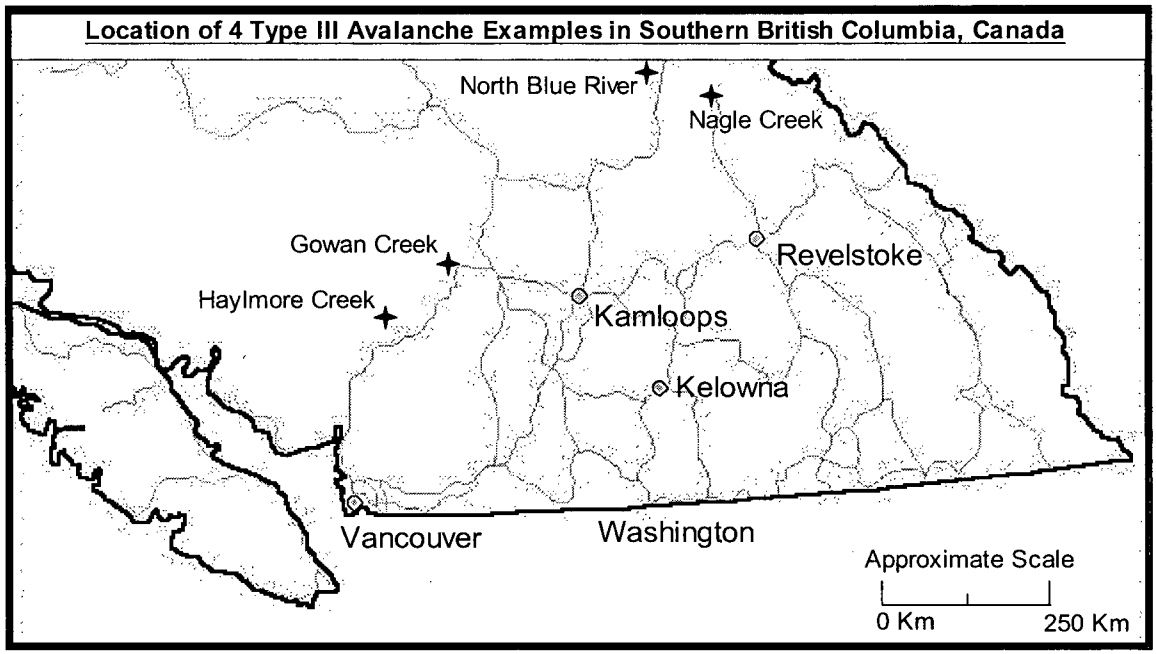


Figure 1.3 TIII case study locations.

1.5.1 Nagle Creek

Major avalanche events have occurred in the Kootenay mountain range (Airy Creek) in 1994, after which the community water supply was jeopardized, the Selkirk range (Alkokolex Creek) in 1996, and the Monashee range (Nagle Creek) in 1996. These incidents have inspired research toward a better understanding of how clear cutting practices influence potential avalanche terrain (Weir, 2002). Nagle Creek was the largest of these events. It is located near the Mica dam, north of Revelstoke, British Columbia. In 1986, an area of approximately 22 ha was clear-cut; it is located in the centre area of the photograph shown in Figure 1.4. The airphoto below was taken in 1985 prior to timber harvesting. Figures 1.4, 1.5, and 1.6 are from a succession of airphotos demonstrating how clear-cut logging has created an avalanche prone slope.

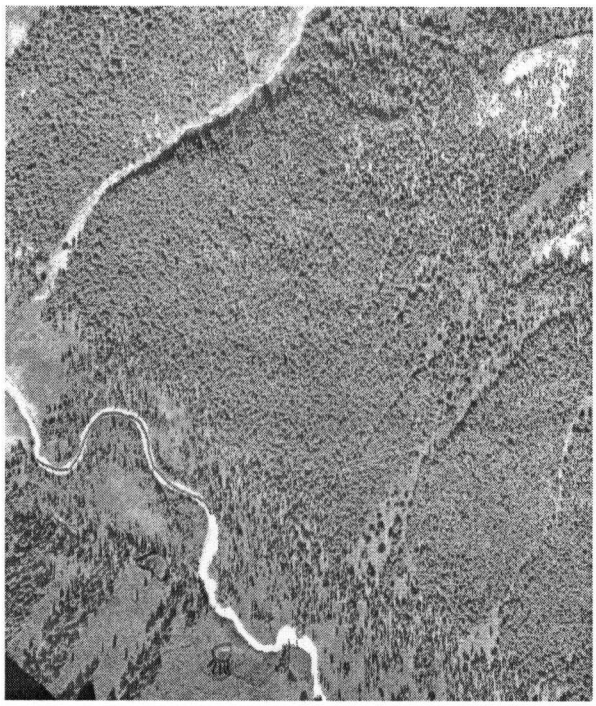


Figure 1.4: Airphoto of terrain prior to logging.

The picture above shows the area to be logged in 1985, prior to logging. The white meandering line in the bottom left-hand side of the photo is Nagle Creek, and the white line from the mid top to the mid left on the photo is a steep gully. The terrain where the cut-block was to be located is relatively planar and is bisected horizontally by a logging road which forms the apex of a vertical convexity spanning the entire cut-block. Figure 1.5 below shows the cut-block after it was cut but prior to the avalanche occurrence. The two lighter areas in the photo are cut-blocks. The central cut-block is cut polygon 27 which avalanched in March of 1996 and resulted in approximately 6.3 ha of the forest cover leave strip being destroyed with a total damage area of 12.4 ha (Stellar Consulting Services, 1996).

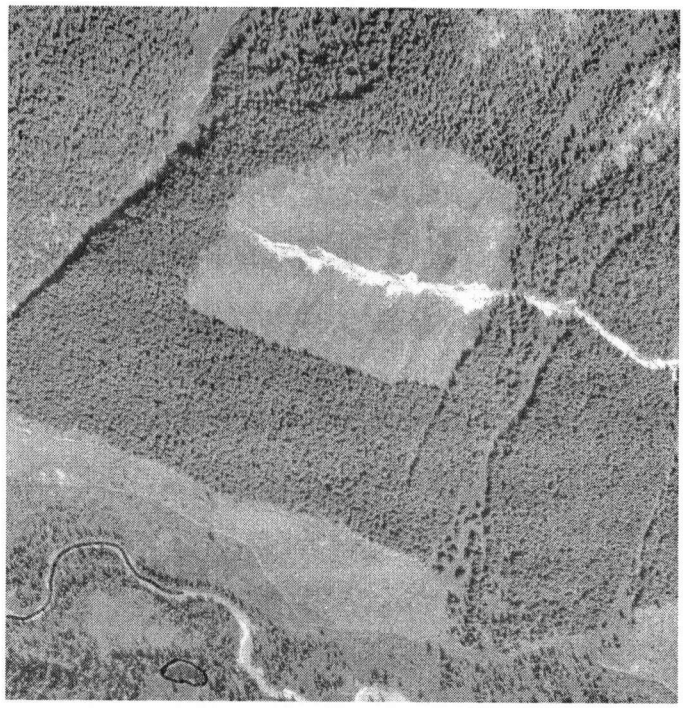


Figure 1.5: Airphoto of cut-block polygon 27, before a large avalanche.

The cut-block was logged in 1988, reforested in 1990 and the photo below, Figure 1.6, was taken in 1997 after a large avalanche destroyed the forest cover protective leave strip between the two cut-blocks in 1996. The avalanche, with an estimated mass of 57 000 tonnes (Stellar Consulting Services, 1996) penetrated through the forest leave strip entraining material down to bedrock, and deposited soil, rocks, and timber into the valley bottom nearly reaching Nagle Creek. The seven white strips in the photo are the swaths destroyed by the avalanche. The photo was taken after the avalanche debris and deposit was cleaned up, so they are not visible in the photo. The swaths where vegetation was removed, readily visible in the photo, now represent potential new avalanche paths.

Figure 1.6: Airphoto of the cut-block after a forest-penetrating avalanche. Seven lobes penetrated through the protective leave strip.

1.5.2 North Blue River

Another large event occurred in the North Blue River drainage, near Blue River, British Columbia. A succession of airphotos is not available; however, Figures 1.7 and 1.8 show site photos of the cut-block after two avalanches. Figure 1.7 shows an initial avalanche that did not significantly penetrate into the forest leave strip. Figure 1.8 shows a subsequent avalanche which did destroy the leave strip and deposited debris into the cut-block below. The photo in Figure 1.7 was taken by the Avalanche Research Group during the summer of 2000. The picture shows the cut-block after an avalanche occurred in the cut-block but did not penetrate forest below the cut except for a small swath on the right-most edge of the cut-block (northern boundary). The north side of the block contains the steepest slope and a small water course down which the avalanche travelled, descending through low density forest into the open cut-block below.

Figure 1.7: Cut-block in North Blue River after a small forest-penetrating avalanche.

Figure 1.8: North Blue River cut-block after an avalanche destroyed 5 swaths through the protective leave strip.

Figure 1.8 above shows the same cut-block in 2003 after an avalanche destroyed the leave strip and cleared an area of approximately 11 ha. The cleared swaths were previously forested with mature cedar and hemlock.

1.5.3 Other Examples

Presented below, in Figure 1.9, are two photos taken after an avalanche at Haylmore Creek, B.C. In the left-hand photo, the perspective is up-slope in middle of the track, the track is gullied and the avalanche cleared a swath ranging from 40 to 55 m in width through standing mature forest. The right-hand photo shows damage sustained by one tree which was not uprooted or snapped during the avalanche.

Figure 1.9. Forest damage at Haylmore Creek, B.C.

Figure 1.10 is a photo taken at Gowan Creek after a large avalanche penetrated through forest cover and destroyed forest below a cut-block (Bauman Engineering, 1999).

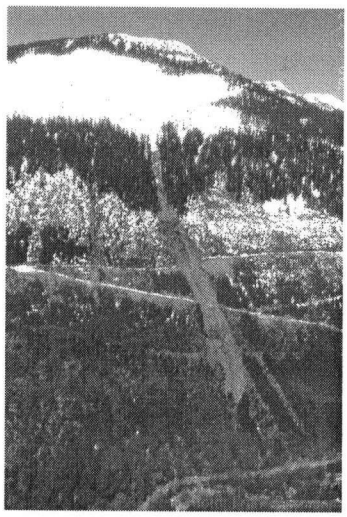


Figure 1.10. Gowan Creek avalanche which destroyed forest cover below a cut-block.

The previous examples are just four of over sixty cases of forest destroying avalanches that have occurred in cut-blocks across B.C. during the last decade. Although this may seem like a relatively small number given the large areal extent of logging in British Columbia, they are not rare events. According to data collected by the ARG on avalanches in more than 300 cut-blocks across B.C., a conservative approximation is that 1/6 of the avalanches occurring in clear-cuts have impacted forest cover down-slope of the clear-cut in some capacity. Most of these did not penetrate through forest and are excluded from this study. Given the large quantity of new cut-blocks created in B.C. every year, many down-slope features across the province may be at higher risk than is presently recognized.

1.6 Conclusion

As clear-cutting continues to be a dominant timber harvesting method used in British Columbia's steep mountainous terrain, better prediction tools are needed to evaluate what risk, if any, is being imposed on forest and other resources below newly created cut-blocks. Forest penetration by avalanches is clearly a problem in timber harvested areas. Natural dynamic systems are being altered, and to date there is not an adequate understanding of the consequences

of logging in this steep terrain. The research presented here is the first attempt to quantify and understand forest penetration by avalanches in order to develop accurate forest penetrating prediction techniques.

Chapter 2: Methods

2.1 Introduction

Snow conditions, snow stability, and climatological conditions are not used in this thesis to predict the potential for forest destroying avalanches to occur, or to predict forest penetration distances. Instead, the physical terrain and vegetation characteristics that can be correlated with the destruction of mature forest are examined. During logging site selection, these characteristics can be selected for or against in order to reduce the likelihood of creating new avalanche terrain with the potential to produce forest penetrating avalanches. Physical terrain characteristics can also be evaluated after harvesting to gauge the potential for forest destroying avalanche occurrence. The probability that an avalanche (once it has initiated) will penetrate forest and reach any given point of interest can also be calculated. The first objective of the methods presented in this chapter was to develop and establish standard quantification techniques to measure and analyze the physical terrain characteristics of newly created forest penetrating avalanches. The second component was to develop a technique to predict runout distances for avalanches running into forested terrain below logging cut-blocks. Data generation and the analysis are outlined in five steps:

1) Identification and definition of the appropriate variables and parameters to measure.

2) Identifying and visiting sites in the field where forest destroying avalanches have occurred to document the physical terrain and vegetation characteristics.

3) GIS modelling to generate data not collected in the field, and to use as a comparison with field data to determine the utility/accuracy of using a GIS for this type of research.

4) Statistical analysis of the data to identify the physical avalanche path terrain characteristics most closely correlated with mature forest destruction.

5) Development of a prediction model to describe the potential runout distances for newly created avalanche paths.

2.2 Variable Identification

In this thesis, the focus is on variables associated with Type III avalanche paths. The variables of interest for this research include and expand on those of the existing Type I and Type II databases (Stitzinger, 2001, and Weisinger, 2004). A list of the variables follows with a description and definition of each. Data collection methods followed and expanded upon those described in McClung (2001) with a focus on physical terrain characteristics. The Type I and Type II analyses were conducted using 40 physical terrain shape and vegetation variables. The Type III database contains the information presented in Table 2.1. Detailed information including accuracy estimates on new Type III and more complex parameters is presented after the table.

Table 2.1. List of Avalanche Path Parameters and Description
N.B.: *Greater detail follows the table.
(SZ = Start Zone, T = Track, RZ = Runout Zone).

	Information/Variable	Description
Location Information	Path ID	Each path was named and numbered to facilitate discussion and easily identify individual cases.
	TRIM and FCS Sheet Location	1:20,000 Terrain Resource Information Map and Forest Cover Survey sheet number (contain topographic and vegetation data).
	UTM Zone	Universal Transverse Mercator map zone location.
	UTM Coordinates	UTM coordinate location.
	Airphoto #	British Columbia airphoto index numbers.
Site Data	Site Photo	Site photos were taken in the field at all avalanche paths.
	Cut Date	Calendar year the cut-block was logged.
	Event Date	Date of avalanche occurrence.

Climate Variables	Snowfall Mean	Mean annual snowfall averaged from point measurements at various meteorological stations.
	Wind Index *	5 part category index used to quantify wind access to the slope and is an indicator of snow loading.
Physical Terrain Variables	Avalanche Size	Canadian Avalanche Size Classification.
	Slope Aspect	Direction the slope faces (°). Accuracy: ± 5°.
	Start Zone Elevation	Elevation at the top of the SZ measured with a GPS on site and more precisely on maps (m.a.s.l.). Accuracy: ± 10 m (vertical).
	Runout Zone Elevation	Elevation at the bottom of the RZ measured with a GPS on site and more precisely on maps (m.a.s.l.). Accuracy: ± 10 m (vertical).
	SZ Area	Area of the start zone (ha). Accuracy: 0.04 ha or 10 % of the area if <0.04 ha.
	SZ, T, RZ Slope	Average slope of each of the three path segments (°). Accuracy: ± 1°.
	SZ, T, RZ Length	Longitudinal distance down the avalanche path measured on maps and in the field (m). Accuracy: ± 20 m.
	SZ, T, RZ Width	Measured on maps and in the field along an elevation contour (m). Accuracy: ± 20 m.
	SZ, T, RZ Cross Slope Shape *	Categorical index describing the degree of confinement (-2 to +2).
	SZ, T, RZ Longitudinal Slope Shape *	Categorical index describing the down-slope concavity or convexity (-2 to +2).
	SZ, T, RZ Surface Roughness *	Categories 1-3 representing the variation in ground roughness excluding vegetation.
Vegetation Variables	SZ, T, RZ Vegetation Type	Tree species in the avalanche path.
	SZ, T, RZ, Vegetation Size	Height of the vegetation (m).
	SZ, T, RZ Vegetation Density	3 part categorical system describing density as low, medium or high.
	Diameter at Breast Height	Average tree trunk diameter measured at breast height (cm).
Type Three Specific Variables	Horizontal Distance to Forest Cover *	Horizontal distance measured on a map from the top of the start zone to the point of forest penetration (m). Accuracy: ± 20 m.

	Path Length to Forest Cover *	Longitudinal distance along the slope from the top of the start zone to the point of forest penetration, measured in the field and/or on maps (m). Accuracy: ± 20 m.
	Vertical Fall to Forest Penetration Point *	Difference in elevation between the top of the start zone to the point of forest penetration (m.a.s.l.). Accuracy: ± 20 m (vertical).
	Horizontal Distance of Forest Penetration *	Horizontal distance from the point of forest penetration to the tip of the runout zone (m). Accuracy: ± 20 m.
	Path Length of Forest Penetration *	Slope distance from the point of forest penetration to the bottom of mature forest destroyed (m). Accuracy: ± 20 m.
	Path Length Below Forest Penetration *	Slope distance from the point of forest penetration to the bottom of the runout zone (m). Accuracy: ± 20 m.
	Vertical Fall of Forest Penetration *	Difference in elevation between the point of forest entry to the bottom of the forest cover destroyed (m.a.s.l.). Accuracy: ± 20 m (vertical).
	Total Path Length	Slope length from the top of the start zone to the bottom of the runout zone (m). Accuracy: ± 20 m.
	Maximum Damage Width *	Maximum width of mature forest damage measured along an elevation contour (m). Accuracy: ± 5 m.
	Slope Angle at Forest Penetration Point *	Slope angle at the point of forest penetration (degrees). Accuracy: ± 1°.
	Forest Cover Age at Penetration Point	Age of the trees at the point of forest entry (yr).
	Density at the Penetration Point	Estimated tree density at the point of forest entry (stems/ha).
	Crown Closure Class at Pen. Point	Percentage of forest canopy closure, proportion of the ground visible from above (%).
	Forest Damage Area	Area of destroyed forest on the ground surface (ha). Error is approximately 0.04 ha.
	Damage Area	Total area damaged by the slide (ha). Error is 0.04 ha. (10 % of the area if damage area is smaller than the summed distance error).

	Damage Type	Description of what was damaged, ie forest, regeneration, logging road, stream etc.
	Alpha (α) Angles *	Angle at the bottom of the runout zone to the top of the start zone (°). Accuracy: ± 1°.
	Beta (β) Angles *	Angle from the Beta point to the top of the start zone (°). Accuracy: ± 1°.

Over 60 variables were collected, calculated, or measured for the Type III analysis. Complex and new Type III variables are described in greater detail below; refer to Figure 1.2 in Chapter 1 for a diagram of the conventional physical terrain variables used in the analysis.

2.2.1 Wind Index

The wind index (Schaerer, 1977) is an indicator of the potential for snow loading in start zones. It is a five part category classification scheme describing the wind access to a slope according to terrain and the presence or absence of forest. The categories are described below in Table 2.2.

Table 2.2 Wind Index Descriptions (after Schaerer, 1977)

Category	Description
1	Starting zone completely sheltered from wind by surrounding dense forest.
2	Starting zone sheltered by an open forest or facing the direction of the prevailing wind.
3	Starting zones in an open slope with rolls or other irregularities where local drifts can form.
4	Starting zone on the lee side of a sharp ridge.
5	Starting zone on the lee side of a wide, rounded ridge or open area where large amounts of snow can be moved by wind.

2.2.2 Cross Slope Shape

The cross slope shape is a five part categorical variable ranging from -2 to +2, describing horizontal slope curvature for the start zone (SZ), track (T), and runout zone (RZ). Measurements of cross slope shape were taken largely on-site rather than in the GIS, due to limits in accuracy of the 1:20 000 scale maps used in the GIS. Negative values represent horizontally convex slope shapes whereas positive values represent concave slopes (gullies). A category +2 is assigned to a slope when the tangent of the angle from the bottom of the concavity to the top is at least 0.5. A +1 value is assigned when the tangent of the angle falls between 0.1 and 0.5. A 0 value cross slope shape expresses slope shapes that are approximately without curvature (tangent is <0.1). Negative values are calculated in the same manner but represent convex slopes. These data were taken from existing TI and TII databases or measured on-site for new paths.

2.2.3 Longitudinal Slope Shape

Longitudinal slope shape is a five part categorical variable measured mostly on-site, and is used to describe the down-slope curvature for each of the slope segments (SZ, T, and RZ). Each segment is broken into two sections at a break in slope and the change in slope determines the appropriate category. Positive values indicate a concavity (the slope angle decreases down-slope); negative values indicate increasing slope angle or convexity. A difference of 15° or greater is assigned a value of 2, a slope change between 5° and 15° is assigned a value of 1, and slope changes less than 5° are assigned 0. These data were obtained from the TI and TII databases and measured for new paths.

2.2.4 Surface Roughness

The surface roughness measure is a 3 part descriptive variable describing the size of ground relief features. A low value (1) represents features <1 m, a medium value (2) represents features 1-2 m relief, and a high value (3) represents features >2 m relief. A surface roughness value was estimated for the start zone, track and runout zone of each avalanche path. Surface roughness data were taken from TI and TII data for existing paths and estimated on-site for new paths.

2.2.5 Distance to Forest Penetration

The horizontal distance to forest penetration was estimated in a GIS. Slope distance to the point of forest penetration was measured on site with a laser range finder. The up-slope measure is defined on the slope by an estimated top of the start zone, the lower boundary is the point of forest penetration. The error in the GIS is estimated to be ± 20 m.; on-site error is significantly less and is estimated as ± 5 m. The on-site measurement error is slightly greater than a simple laser measurement (± 1 m) since the exact point where forest existed before the slide was often difficult to define within 5 m.

2.2.6 Vertical Fall to Forest Penetration Point

Vertical fall was measured in metres from the top of the start zone to the point of forest penetration. The measure was taken by subtracting the elevation of the forest penetration point from the elevation at the top of the start zone. Values were roughly obtained on site with a hand held GPS unit, then confirmed or corrected on 1:20 000 scale topographic maps. The values were calculated in metres above sea level and the estimated error is ± 20 vertical metres.

2.2.7 Distance of Forest Penetration

Horizontal and slope distance between the point of forest penetration and the bottom of forest destruction were measured on site and/or in a GIS. The value may differ from the path length below forest penetration since some avalanches may have completely penetrated through leave strips while others may have stopped within the leave strip. This value represents only the distance of forest penetration, excluding any distance travelled below mature forest cover. Error is estimated as ± 20 m in a GIS and ± 5 m for on site measurements.

2.2.8 Path Length Below Forest Penetration

The distance below penetration is the full path length below the forest penetration point, it is the full distance travelled by the avalanche after it penetrates forest cover. Some avalanches ran beyond the bottom of mature forest destruction into separate cut-blocks or open areas. The full path length below forest penetration is the distance from the forest penetration point to the bottom of the runout zone. In some cases, when avalanches stopped under the cover of mature forest, the distance below forest penetration and distance of forest penetration are the same. The error here is also estimated as ± 20 m in a GIS and ± 5 m for on site measurements.

2.2.9 Vertical Fall of Forest Penetration

The vertical fall of forest penetration was taken by subtracting the elevation at the toe of the runout zone from the elevation at the forest penetration point. Error is ± 20 vertical metres.

2.2.10 Maximum Damage Width

The maximum width of damage through forest cover, measured parallel to elevation contours was measured with a laser range finder or in a GIS. The value represents the maximum lateral spread once the avalanche enters forest cover; error is ± 5 m.

2.2.11 Slope Angle at Forest Penetration Point

The slope angles at the point where the avalanche first entered and penetrated forest cover below the cut-blocks were measured with a clinometer. Angles were measured in degrees and are accurate to ± 1°.

2.2.12 Age of Damaged Forest

The age of forest destroyed at each site was taken from Forest Cover Survey sheets in order to assess the loss sustained from forest destroying avalanches and to determine whether or not there is an age specific susceptibility to destruction. Age class is a 9 part categorical classification that classifies forest stands according to the age of the stand. The classification places forest stands in groups of 20 years.

2.2.13 Crown Closure Class (CCC)

CCC is the best proxy for forest stand density for these data. CCC is an 11 category classification found on Forest Cover Survey Sheets (FCS) describing the percentage of ground covered by vegetation. It is estimated vertically from above.

2.2.14 Damage Area

The area of destroyed forest was measured using the average width and length measurements taken with a laser range finder or on a GIS. Areas are expressed in hectares and the error is ± 0.04 ha. For damage areas less than 0.04 ha, the error is estimated to be 10 % of the measurement.

2.2.15 Alpha and Beta Angles

Alpha (α) and Beta (β) angles were measured with a clinometer, and are accurate to $\pm 1°$. The Alpha angle is the angle at the toe of the runout zone to the top of the start zone. The β point is defined as the point on the slope that first becomes 10°, down-slope of the start zone. Beta angles were taken as the angle at the β point to the top of the start zone (Figure 1.2).

2.3 Forest Cover Defined

The premise of this study is that the presence of mature forest cover in the track and runout zones may reduce avalanche runout distances. Since the age, size, and species of forest vary greatly across British Columbia, a definition of what constitutes forest cover is necessary. Relatively young, weak forest is not included since its influence on the runout of an avalanche is expected to be minimal (Weir, 2002) and has little or no effect on the behaviour of avalanches. For the purpose of this study, forest cover is defined as living forest that is at least 5 m in height. This definition is important as re-growth in existing paths is often prevented annually by high frequency avalanches, and this re-growth is not substantial enough to be considered mature forest. It is assumed the re-growth (alder or young replanted coniferous forest) has a minimal influence on avalanche behaviour and, therefore, is not of interest to this study.

The 5 m minimum height value was used to avoid the use of an age definition since trees of the same age can vary greatly in height for different species and growing conditions. Tree growth rates vary greatly across British Columbia according to available soil nutrients, soil depth, elevation, species type and other factors. Using a 5 m minimum height cut-off rather than an age definition ensures that, at the time of the avalanche, there was sufficient trunk length protruding above the snow surface in winter to interact with avalanche motion. This also confirms that the trees existed in the same location for a significant period of time (it can be roughly assumed that a 5 m tall tree has lived for a minimum of 20-30 years).

At approximately 5 m there also seems to be a division in the manner in the way trees react to the impact forces of avalanches. Data collected for this research suggest that trees shorter than 5 m tended to bend when struck by avalanches, and trees taller than 5 m tended to be broken or overturned upon the impact of an avalanche. It is assumed that bending trees have little effect on the flow when overrun by an avalanche. The definition for forest cover in this study, then, is any living forest in the track and runout zone that was at least 5 m tall at the time of the avalanche occurrence.

Forest damage is a somewhat ambiguous term. There are many damage classifications for forest depending on how the trees have been damaged. Damage can occur from avalanches that will render timber un-harvestable. Examples of forest damage include topping, scarring or girdling, and defoliation. Topping occurs when the tops of trees have been broken off and left with a dead top or a fork. Severe scarring or girdling on the upslope side of trees can stunt growth and/or kill trees. Finally, flagging or defoliation occurs when the trees are stripped of branches on the upslope side by snow flowing around the trunk but not uprooting the tree. In this work, damage refers only to the most severe cases for which trees have been uprooted, overturned or snapped by an avalanche.

2.4 Avalanche Path Identification

Personal communication and airphoto searches were the primary methods to identify the location of recent forest destroying avalanches. In areas where there is helicopter skiing, the primary source of reports is the ski guiding community. In other areas local avalanche forecasters, consultants and others working in the field have identified potential study sites. For some areas where extensive logging is being conducted on steep slopes (for example the North Blue River and Thunder River Drainages), searches through recent airphotos were successful in identifying potential study sites. Potential study sites were confirmed by field visits conducted during the summers of 2002, 2003 and 2004.

2.4.1 Study Area

Avalanche paths used in the analysis are Type III avalanche paths (those that have penetrated and destroyed forest cover) which have occurred over the last decade; they are distributed around southern British Columbia. The dataset contains 45 individual paths at 24 sites in British Columbia. Figure 2.1 shows the location of the 45 avalanche sites in the Southern Coast and Columbia Mountain ranges of B.C.

The study site distribution in Figure 2.1 appears to be skewed towards the Coast Mountain Range. However, the path distribution is approximately equal between the Coast and Columbia Ranges. In Figure 2.1, there are multiple paths represented by individual points with 20 cases in the Columbia Mountains and 25 in the Coast Mountains.

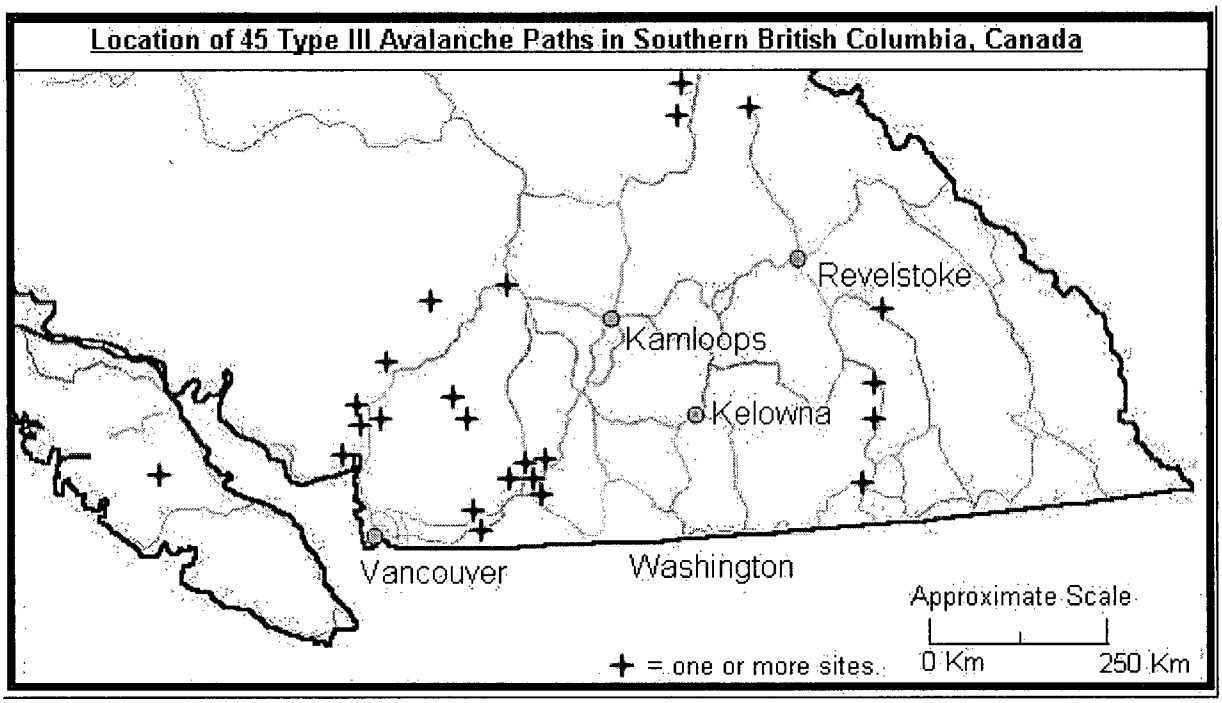


Figure 2.1. Location of 45 Type III avalanche study sites.

The cases are combined into one group for the analysis for two main reasons. First, there are not enough data points in solely the Coast or Columbia ranges to produce results with any significant confidence, whereas forty five cases distributed across B.C. is a large enough sample to conduct valid statistical analyses. Second, since the analysis deals only with physical terrain parameters and not snow conditions, stability or meteorological conditions, then the only major difference (other than the terrain features themselves) is the forest species. Since the forest type varies greatly between paths even within the same mountain range, it is impossible to subdivide the database according to forest type since comparison for so many types of forest would yield data groups which are too small.

2.5 Data Collection and Generation

2.5.1 Tools and Data Sources

The basic tools employed to collect and generate the data were a hand held GPS unit (Garmin etrex), a Suunto clinometer, a Bushnell Laser Range Finder, Digital and Hard Copy Terrain Resource Inventory Maps (TRIM) and Forest Cover Survey Sheets (FCS), Stereo Airphotos, Site Photos, and a Geographic Information System (ArcView 3.2).

2.5.2 Field Methods

The field work to complete the project was time consuming but relatively simple. Since the avalanche paths were spread across southern British Columbia, general access was relatively easy by highway. During the summers of 2002, 2003, and 2004, recent TIII and some older TI and TII avalanche sites were visited (for which TIII variables had not previously been documented). For sites that were inaccessible by pickup truck, access was obtained by bicycle or on foot. For a small number of very remote cases, overnight stays on-site were necessary. Field work was completed by two people in order to facilitate measurement taking. The most reliable measurements of distances and angles are taken with a partner since the observer can sight off his/her partner to ensure there is no loss of slope angle or distance from estimating the height at which to site off an object. Variables were measured on site and later used to confirm or correct measurements made in the GIS.

2.5.3 GIS Methods

Geographic Information Systems (GIS) are powerful tools that allow the investigation and analysis of spatial data in ways that are not possible with conventional database management systems or physical hard copy (paper map) approaches. GIS allows the layering of maps and

attribute information to facilitate the analysis and query of data over multiple layers in a way that paper maps cannot be used. A GIS was used to support this research because the output is compatible with a number of different computer applications, and management of the data is relatively easy and efficient.

A GIS is desirable to minimize error in map use and maximize procedural efficiency since the data set is large for hard copy methods. Large data sets can be relatively easily manipulated and spatially analyzed with GIS programs compared to other database management systems. Using a GIS in this project also returns data and allows its storage in a format that can be used in the future for dynamic flow model development, tuning, and calibration, as well as statistical modelling.

2.5.4 GIS Modelling Procedure

The first task to accomplish was to establish the location of the Type III avalanche paths and enter the appropriate maps into the GIS. Specific path locations were established on airphotos and maps after suspected study locations were identified. Site visit descriptions including written descriptions of the damage and the topography were used to locate the avalanches on a topographical map. Since most avalanches tend to follow the path of least resistance (usually a stream or creek bed), locating the path site on a digital elevation model (DEM) or contour map is usually relatively simple.

'Locator points' (features that are easy to recognize and are common to both the photos and maps) were identified on the airphotos and site photos to provide reference points in order to digitize the paths on the TRIM and FCS sheets. Examples of locator points used in this project are the intersection of two or more roads, curves and corners in roads, the intersection of creeks, meanders in creeks, cut-block perimeters, ridges, and valley bottoms. The perimeters of the

avalanche paths were drawn onto the airphotos and the centre line was marked in order to extract a slope profile.

The point of avalanche interaction with forest cover was determined according to terrain features identifiable on the airphotos and TRIM sheets as well as field note descriptions. Identifying logging roads, landing points, forest and cut-block boundaries, and valleys is relatively simple on these maps and photos. These features, in combination with field data, were used to locate and delineate the avalanche paths.

The next step was to digitize the avalanche boundaries into the GIS. Once locator points were identified, they were marked manually on the TRIM sheets as reference points. Since most avalanches travelled down easily identifiable creek beds or gullies, the digitization of the centre line of the avalanche path was also relatively easy. The start and endpoints of the avalanche were first identified with field records of elevation and site description. A more accurate estimate of starting and ending (top of the SZ and toe of the RZ) positions was subsequently made by identifying terrain features on the air and site photos that were noted during the site visit and using them to precisely delineate the start and end point locations. This method is more accurate than simply using a GPS unit reading since the elevation error on the GPS unit is relatively high. Little error is incurred here in terms of laterally misplacing the path because the terrain features followed by the avalanches were usually easily recognizable on the TRIM sheets and DEM.

The greatest level of inference occurs for paths where photos were available for the terrain only before or after the avalanche occurrence. In some cases the airphotos were taken before the avalanche event occurred so the actual path of travel through forest was extremely difficult to place. In spite of site photos existing for all the paths, placing the avalanche path boundaries is a best estimation because the photos are not in plan view (they were taken from the

ground rather than the air). Polygons representing the perimeters and damage areas were estimated and drawn using site photos and field descriptions. The areas of these polygons were calculated in ArcView and exported to the paths' attribute tables.

2.6 A Modelling Example

2.6.1 Delineating Polygons

Nagle Creek is used as an example here because it is probably the most widely studied avalanche event occurring in a cut-block during the last ten years. As a result, nearly ideal data are available for these seven avalanche paths and therefore it is a good location to demonstrate the process. The example in Figure 2.2 shows terrain features that are easily distinguishable and provide good locating points.

Figure 2.2: Example of a scanned airphoto showing 7 forest destroying avalanche paths.

The cut-block boundary, the river, logging road and gullies are easily visible in Figure 2.2 but the gullies are not readily identifiable from the contours in Figure 2.3 below. Figure 2.3 is a screen shot of Arcview 3.2, containing the TRIM and FCS terrain data without the digitized avalanche paths. The 1:20 000 scale of the TRIM map containing the contours in Figure 2.3 and 2.4 is too coarse to show the somewhat gullied nature of the cut-block.

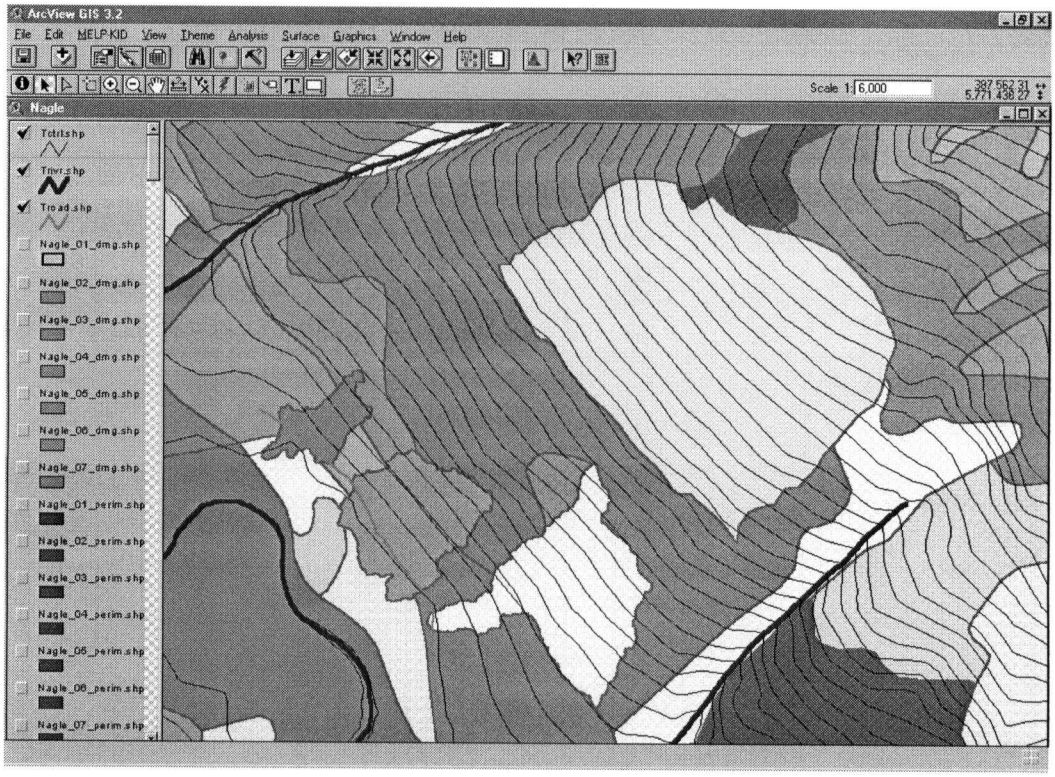


Figure 2.3: Nagle Creek forest polygon 27 (light) with easily discernible locator points (cut-block corners, rivers, logging road).

The next step was the digitizing of the paths themselves, and is shown in Figure 2.4. From the digitized boundaries, slope profiles, distances, and accurate measurements of areas can be extracted from the polygons and exported into a spreadsheet for statistical analysis.

It should be noted that the avalanche path boundaries shown in Figure 2.4 are estimates. In reality, the fracture line initiated a slab avalanche that extended across the entire width of the cut-block. Once in motion, the avalanche was separated into seven lobes which were defined by

gully features within the block. It is necessary to estimate and delineate definite path dimensions (for example start zone width and length) in order to model the paths statistically and in a GIS. To accomplish this, each forest penetrating lobe was treated as a separate path and the boundaries of each path were estimated.

Figure 2.4: DEM showing digitized path perimeters extending below the cut-block into the forest leave strip.

2.6.2 Extracting the Profile

The profile extractor is an avenue extension program that adds the Profiler extension to ArcView; using this method rather than hard copy approaches significantly reduces the time needed to generate a profile. When activated, the profile extractor reads from a grid surface using 3D Analyst and Spatial Analyst. The grid can be loaded into ArcView from a DEM or created from contour lines, both of which are available in digital TRIM data. The grid interpolates elevations between contour lines allowing the profile extractor to read from a

continuous surface rather than point locations on contour lines. The profile extractor exports UTM co-ordinates and corresponding elevation values (X,Y,Z) to the attribute table of a line or a series of points digitized by the user. Elevation is reported to the nearest centimetre by the profile extractor but is limited in accuracy by the DEM. The elevation models used in this research define accuracy as 90% of all well defined planimetric features to be within 10 m of their true position and 90% of all points interpolated from DEMs including contour data to be accurate within 10 m of their true elevation (Government of British Columbia, 2005).

2.7 Analysis

A number of analytical approaches were taken in this research with the original goal of comparing and contrasting different methods of runout predictions. The nature of the dataset forced a narrowing of the focus to runout ratio analysis which is the most useful and provides the best results here. Statistical correlation analyses were conducted, and standard runout ratio methods were applied.

2.7.1 Descriptive Statistics and Statistical Correlations

Cumulative distribution functions, quantile plots, probabilistic distributions and bar charts are used to present the distribution of variables closely linked to forest penetration. Regression plots were created for individual and combinations of variables to try to correlate damage extents with these variables. Paired t-tests were used to establish whether there were significant differences between means for like variables in different databases (for example TI and TII), and tests of normality were conducted in Systat 10. All plots were created using Microsoft Excel, Systat 10, and Grapher. Databases were managed in Microsoft Access, Microsoft Excel, and Systat 10.

2.7.2 Runout Ratios

Runout ratios were calculated for different points of reference on the avalanche slopes. Historically, Beta (β) point analysis has been used extensively to predict the probability of an avalanche reaching a given point on a slope. The β point is used to calculate a runout ratio ($\Delta x/X_\beta$); the runout ratio can be fit to a probability distribution to predict the probability of an avalanche reaching a point down-slope of the β point. Runout ratios were calculated here for two reference points on the slope. A 10° β point was used as well as the point of forest entry.

The runout ratio $\Delta x/X_\beta$ in this research was calculated by dividing Δx, the horizontal or slope surface distance from the β point to the bottom of the runout zone, by X_β, the horizontal or slope distance from the top of the start zone to the β point. Forest entry point runout ratios were calculated in the same way for the ratio $\Delta f/X_F$ (Figure 1.2).

2.8 Limits in Accuracy

This work is part of ongoing research that began in 1996. During the last 8 year period many different researchers have contributed to this work. Standard measurement techniques have been developed by the Avalanche Research Group and an effort has been made for new researchers to be trained by experienced group members. In spite of this, there are differences in perspective among researchers, and variables which require judgement calls on the part of the surveyor. These factors can result in slightly different values being reported for the same terrain.

Most of the data have been collected in the field (which is most reliable) but some gaps have been filled with the use of TRIM and FCS maps in a GIS. Although the use of the GIS reduces the potential for error compared to hard copy methods, it is not as accurate as data collected in the field. Terrain variations evident in the field are often absent from the detail of 1:20 000 scale maps. Small gullies, ridges, and rolls are often undetectable on the maps but are

significant enough in reality to alter the avalanche behaviour; an example of this is the Nagle Creek event (refer to Figures 2.3 and 2.4). This should serve as a caution to researchers using maps to develop databases such as the one used here, field verification is necessary in order to confirm the bounds of error and to ensure the terrain is being assessed correctly. A short discussion on the advantages, disadvantages and error associated with the use of a GIS follows in chapter 3.

Chapter 3: The Utility of Using a GIS in Avalanche Research

3.1 Introduction

GIS is a powerful analytical tool for geographical spatial analyses. This project could have been accomplished with conventional paper maps rather than in a digital format on a computer. In some cases, due to the unavailability of digital maps, the procedure was conducted by hand. As a user it is easy to become enraptured with the lure of GIS to undertake research of this nature. It is dangerous to assume that digital, computerized methods are automatically faster, easier and more efficient than hand drawn 'analogue' methods. The following discussion explores the benefits and drawbacks to each approach encountered in this research.

3.2 Limits of Hard Copy vs. Digital Approaches

Hard Copy Maps

1:20 000 scale is the largest scale available (1: 10 000 is sometimes available but not for this project). The resultant human calculation error is ± 10 m corresponding to ½ the smallest measurement unit (1 mm).

Folds and stretching in paper maps creates distortion of the true distance. Fold lines and stretching are significant sources of error on hard copy maps if they have been folded. Stretching a map by 1 mm results in a measurement error of 20 m in addition to the normal error incurred in physical measurements.

Themes from which information is drawn, such as cut-block size, forest type, forest density and vegetation size, cannot be portrayed in any other format than is already printed on the paper maps. It is not possible to query information on paper maps as it is in the computer models.

Digital Maps

Computing power and storage space (which are becoming less of a problem as technology progresses and prices decrease) can be limiting. TRIM maps and DEMs require significant storage space; the project completed here (not an exceptionally large one), required at least 7 GB of storage. Computer processing speed can limit the GIS program's ability to complete tasks. The data returned were not difficult for the computer to calculate but the size of the TRIM maps and FCS sheets occasionally caused the system to become overloaded and 'freeze' as a result.

The cost of completing a project such as this is much greater using a computer/digital approach compared to a paper approach. Paper maps cost approximately $5.00 per mapsheet, whereas mapsheets (with DEMs) purchased in digital currently cost $400.00 to $500.00 (Government of B.C., 2003). GIS programs are also expensive; ArcView 3.3 currently costs approximately $1800.00 and necessary extension files can increase the program's price by thousands (ESRI, 2003). In a research environment these resources may or may not be available, so the researcher will be bound by funding and resource availability.

3.3 Advantages of Approaches

Hard Copy Maps

Paper maps are relatively simple to use compared to computer maps, especially for researchers who lack strong computer skills. They are cheaper to purchase, and work can commence as soon as the map is acquired since there is no need to configure the project or set up directories as must be done when using a GIS.

Digital Maps

Digital maps are desirable when large projects are being undertaken. The digital format facilitates the storage of data as well as speed and efficiency when multiple maps are being considered. Digital maps allow manipulation of the data themes' characteristics such as colours and classification which is not possible in any simple manner with paper maps. Queries can also be performed in GIS programs that would be impossible on paper maps. Finally, higher resolution information is available and the data can easily be added to or manipulated by the user.

3.4 Airphoto Considerations

Using Scanned Photos vs. Physical Prints

Scanned airphotos were used in this analysis, but consideration should be given to the benefits of using physical stereo pairs of airphotos. Neither scanned digital nor physical photos are orthonormal without correction, as the photos were originally taken in stereo pairs. Single airphoto use on a computer screen and printed versions each result in the same directional and distance error. The benefit of using a GIS program is the tilt can be corrected for, using a program such as AirPhoto. The photo can then be draped over digital elevation models using 'locator' points, such as were earlier described, and a technique called 'rubber sheeting'. The result is a three dimensional view of the terrain, but detail is lost relative to the use of stereo pairs.

Resolution depends on the resolution of the airphoto and the scanning resolution used to enter the photo into digital form. Resolution of the photos used in this project was approximately 1: 15 000. The advantage of using printed stereo pairs is that the terrain can be viewed in three dimensions with much greater detail than a single photo warped over a DEM.

However, a GIS allows 'zooming' in on a photo in order to see better detail and thus allows the user to digitize points and lines with greater precision.

3.5 Error

Accuracy on paper and digital 1:20 000 scale TRIM and FCS sheets is within 10 m of true location. Since a point must be placed at each end of the avalanche path to delineate its location on the map, a digitised path has a longitudinal error of 20 m. Measurement accuracy in the use of paper maps has an additional error factor. It is determined by half of the distance of the smallest measurement unit, in this case the smallest measurement unit would be 1 mm; 0.5 mm corresponds to 10 m on a 1:20 000 scale map. When the two sources of error are combined (error in the map and measurement error) the total error for a path length distance measurement is 40 m. In this project the paths are generally longer than 1 km, and so, 40 m is an acceptable range of error. However, for short-slope paths, 40 m may not be an acceptable error.

Digital maps do not have the same problem since there are no measuring device units, only points digitized on the screen. There is no width or length dimension to a point on the computer screen as there is when a point is drawn on paper. Measurement on paper is limited by the width of the mm mark on a ruler and the diameter of a pencil tip. The scale of the digital maps used in this research, could be increased in most cases to 1:5 000 or even greater depending on computer screen size and the length of the avalanche path, thus allowing the user to place points much more precisely and accurately than would be possible on paper.

3.6 Conclusion

While a GIS can be used effectively for avalanche research of this type, it must be used carefully. The scale of maps used here (1:20 000) does not allow great enough surface resolution to calculate accurate cross slope shapes. General features are visible, but smaller features that

have been noted in the field to change the behaviour of an avalanche are not apparent on 1:20 000 scale maps. There was some use of 1:5 000 scale maps in this work but even at this scale gully features that could influence avalanches were not always apparent on the maps. A reason for this could be that the large scale map was developed from a smaller scale map.

In this research the best use for the GIS was to make distance measurements, calculate average slope angles over significant distances and to calculate areas. A GIS used at a 1:20 000 scale is inadequate for calculating cross or longitudinal slope shapes. There were instances where small gullies had produced or augmented avalanches so that they were able to penetrate forest cover, but these gullies were not visible on the maps. Only field visits revealed the presence of these gullies.

A GIS is a useful tool to increase the efficiency of measurement and to develop a database quickly. A GIS can not be used as a substitute for field work and should be used with careful note of the limits inherent in the use of remote data.

Chapter 4: Analysis

4.1 Introduction

In this chapter the results of the analysis are presented. The objective of the analysis was to ascertain which terrain characteristics exhibited the best correlation with the extent of mature timber damage and forest penetration and to use those characteristics to develop runout and damage prediction techniques. When the variables most closely correlated to forest damage were identified, they were used to develop prediction procedures to assess the potential for new avalanche terrain to produce forest penetrating avalanches. It was quickly determined that no single nor combination of slope or vegetation characteristics (such as slope angle, terrain shape, vegetation density and size, and other variables listed in Table 2.1) could be used to predict the potential extent of damage, and so the focus of the analysis adapted largely to a descriptive and probabilistic predictive nature.

Bar chart distributions, cumulative density functions, quantile plots and probability plots are used to describe the variables characterizing forest penetrating avalanches. Runout ratios were also calculated which can be used to estimate the likelihood of new avalanches descending to predetermined points on a forested slope. Terrain shape can also be used to estimate the potential for lateral spread of avalanches when they encounter mature forest cover in the track and runout zones.

Properties of each of three average path segments (the start zone, track and runout zone), are described and analyzed. The focus of this analysis is on the lateral and down-slope distance travel potential for avalanches in forested terrain. Since the thesis is not concerned with the initiation of avalanches, the study first focused on the retarding effects of terrain (slope angles, slope shape, etc.) and forest in the track and runout zone.

Of over 300 documented avalanches occurring in and around timber harvested terrain in southern British Columbia over the last 10 years, at least 60 had some significant interaction with forest cover. The database for this analysis is comprised of 45 forest penetrating avalanches; all meet the criteria defined in Chapter 2 in order to qualify as a forest penetrating avalanche.

4.2 Results

Table 4.1 is a statistical summary table of the path characteristics for the entire TIII database. This table allows comparison to other databases to show the physical differences between forest penetrating avalanches and non-forest penetrating avalanches. Significantly skewed values are presented in italics, all other values exhibit a normal distribution. Values in bold text represent a distribution that exhibits significant kurtosis, non-bold text indicates a normal distribution.

The statistics presented in table 4.1 were calculated using Systat 10. Skewness is defined as a measure of the symmetry of a distribution about its mean. If skewness is significantly nonzero, the distribution is asymmetric. A significant positive value indicates a long right tail; a negative value, a long left tail. A skewness coefficient is considered significant if the absolute value of skewness/SES is greater than 2. SES is the standard error of skewness and is defined as (SQR(6/n)). SES for these data equals 0.354.

A value of kurtosis significantly greater than 0 indicates that the variable has longer tails than those for a normal distribution; less than 0 indicates that the distribution is flatter than a normal distribution. A kurtosis coefficient is considered significant if the absolute value of kurtosis/SEK is greater than 2. SEK is the standard error of kurtosis and is defined as (SQR(24/n)). SEK for these data is equal to 0.695.

Table 4.1 Statistical Summary of Forest Penetrating Avalanche Characteristics.

Path Segment	Property	N	Min.	Max.	Range	Mean	St. Dev.	Skewness	Kurtosis
START ZONE	Slope (°)	45	20	50	30	36	5	-0.54	**3.31**
	Cross Slope Shape	45	0	2	3	-	-	-	-
	Width (m)	45	40	680	640	161	125	*2.5*	**8.3**
	Length (m)	45	75	1050	980	290	212	*1.5*	**2.4**
TRACK	Slope (°)	45	23	41	18	33	4	-0.57	0.59
	Cross Slope Shape	45	-1	2	4	-	-	-	-
	Width (m)	45	15	250	235	59	47	*2.4*	**6.8**
	Length (m)	45	140	1050	910	445	211	*1*	0.54
RUNOUT ZONE	Slope (°)	45	4	34	30	22	6	-0.36	0.32
	Cross Slope Shape	45	-2	2	5	-	-	-	-
	Width (m)	45	10	250	240	60	46	*2.2*	**6.7**
	Length (m)	45	47	720	673	216	118	*2.2*	**7.1**
TRACK TO RUNOUT ZONE TRANSITION	Cross Slope Shape Difference	45	-3	1	4	-	-	-	-
	Lateral Spread Ratio	45	0.2	3	2.8	1.2	0.66	*1.2*	**1.1**
	Lateral Spread (m)	45	-120	55	175	1	29	*-1.5*	**5.5**
FOREST PENETRATION PARAMETERS	Vertical Fall to Penetration (m)	45	70	800	730	308	180	*1.4*	**1.6**
	Path Length to Penetration (m)	45	252	1799	1550	715	410	*0.95*	0.11
	Path Length Below Penetration (m)	45	2	1250	1250	405	280	0.56	0.23
	Slope at Penetration (°)	45	4	45	40	28	10	-0.1	-0.37
	Forest Entry Runout Ratio	45	0.002	2.85	2.85	1	0.75	-	-
	Damage Area (ha)	45	0.02	6.3	6.3	2	1.4	-	-
FULL PATH LENGTH	Total Vertical Fall (m)	45	190	870	680	490	180	0.39	-0.56
	Total Path Length (m)	45	370	1840	1470	1004.1	390	0.58	-0.44
	Beta Angle (°)	45	20	35	15	29	3	-0.34	0.4
	Alpha Angle (°)	45	21	36	15	30	3	-0.45	0.62
	Runout Ratios	45	-0.8	0.07	0.87	-0.2	1.3	*-1.37*	1.857

4.2.1 Avalanche Track Characteristics

The risk of avalanche initiation was quantified in the analysis of Type I data and is not of concern here. Once an avalanche has been triggered and is in motion, the track is the first path segment to interact with the slide. Track characteristics were examined carefully since avalanche

speeds are most likely at their maximum, and terrain and vegetation characteristics in the track are the first variables which have an opportunity to change the avalanche behaviour. No single track parameter could be correlated to the extent of forest penetration or areal extent of damage through linear regression plots with any reliable significance. Combinations of various parameters (such as track horizontal slope shape multiplied by average track slope angle) lead to insignificant relationships between the combined variables and either forest penetration distance or damage areas. Results from analysis of the track characteristics are presented below.

Track Slope

Figure 4.1 contains the distribution of average slope angles in the track for 45 forest penetrating avalanche paths.

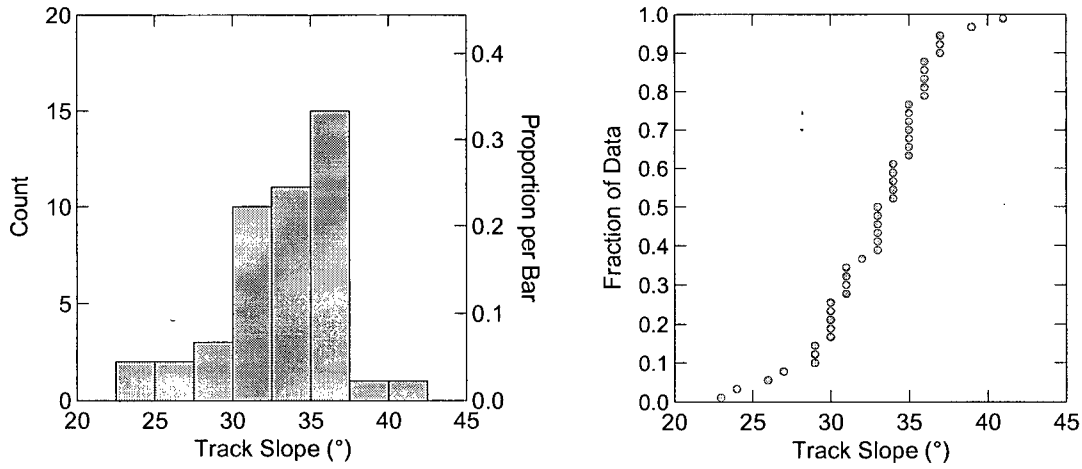


Figure 4.1 Density and Quantile plots of track slope angle for forest penetrating avalanches.

Approximately 90 % of the track average slope measurements fall between 29° and 37°. The range is 23° to 41° with a mean of 33°, the standard deviation is 3.6. The average TI and TII track slopes are 32° and 35° respectively. The track slopes are slightly higher than typical values for avalanche slide paths across British Columbia (McClung and Schaerer, 1993).

Track Cross Slope Shape

Cross slope shape categories range from –2 to +2, a 0 value indicating a slope with no cross slope curvature. The density histograms in Figure 4.2 show all but one example to be of slope shape 0 or greater. In other words, except for one case, all track horizontal slope shapes are gullied or exhibit no cross slope positive curvature; there is only one occurrence of horizontally convex terrain producing a forest penetrating avalanche. A large proportion (42%) fall into class 2 CSS in the track; this is the highest gully classification possible. Since there is only one occurrence of horizontally convex terrain shape in the track that produced a forest penetrating avalanche it is reasonable to say that concave terrain presents a greater likelihood of forest penetration. The propensity for avalanches to occur on horizontally concave terrain may be a result of cut-block location rather than avalanches tending to slide on concave terrain. This is not evident in the data since only cut-blocks that experienced avalanches are contained in these data.

The TIII dataset is biased closer to the TI data since most of the Type II avalanches which did descend into a clear-cut did not have sufficient energy to travel through the cut-block into the forest below. The TII data contain large scale avalanche paths that typically terminate within cut-blocks and for that reason there are only 6 TII paths included in the TIII analysis.

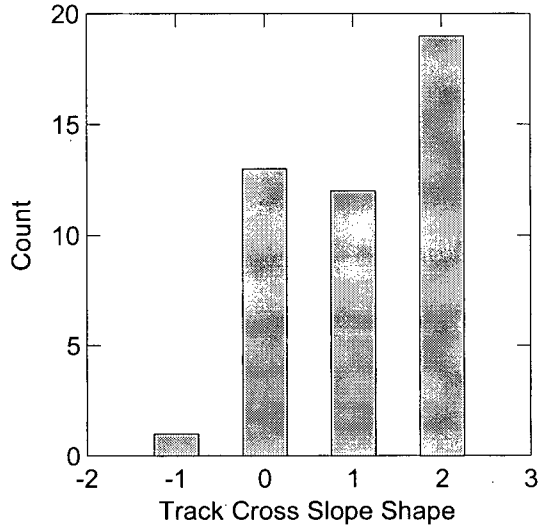


Figure 4.2 Bar chart plot of track cross slope shape for forest penetrating avalanches.

Track Width

Figure 4.3 contains the distribution of average track width measurements.

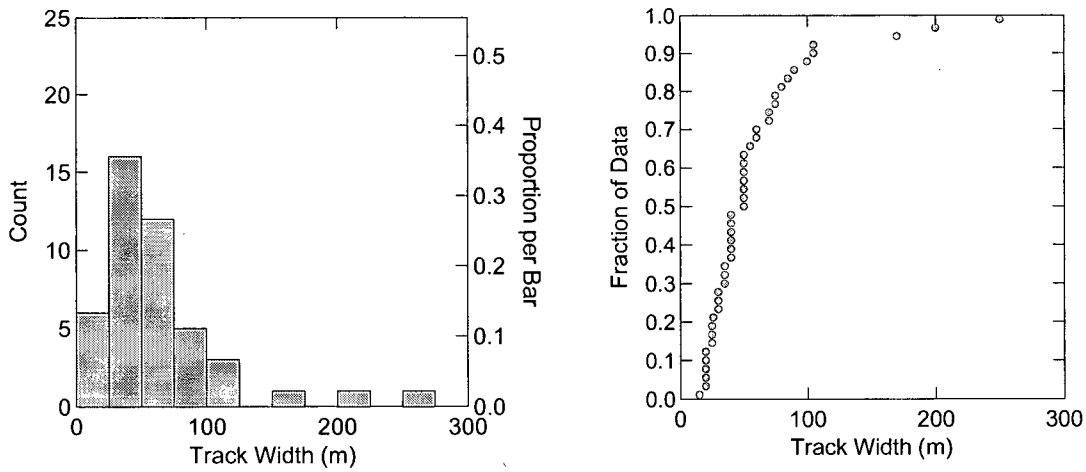


Figure 4.3 Density and Quantile plots of track width in metres for forest penetrating avalanches.

In the track, 89% of the widths are 100 m or less and 71% are 60 m or less. Three extreme cases were measured at 170 m, 200 m, and 250 m wide. These cases each contained relatively wide start zones and tracks as well as runout zones. In addition, they were not

significantly funnelled from the start zone into the track, or from the track into the runout zone. The data suggest that the slides on slopes with no horizontal curvature stopped at the lower block boundary or within a few metres of entering forest cover, possibly this was because the energy of the slides was not focussed into gullies. Overall, the track widths are relatively narrow compared to TI and TII datasets (Stitzinger, 2001, Weisinger, 2004), and the start zones appear to be fairly typical in width. The result suggests that the forest penetrating avalanches tend to have their energy focussed into relatively narrow tracks as they descend into forest.

Track Length

The track length in this database cannot be used as a predictor for potential damage. Linear regression analysis indicates that track length alone is not related to damage area or penetration distance. The distribution, however, is useful for documenting the range of forested track lengths that can be penetrated by avalanches. Figure 4.4 shows the track length distribution.

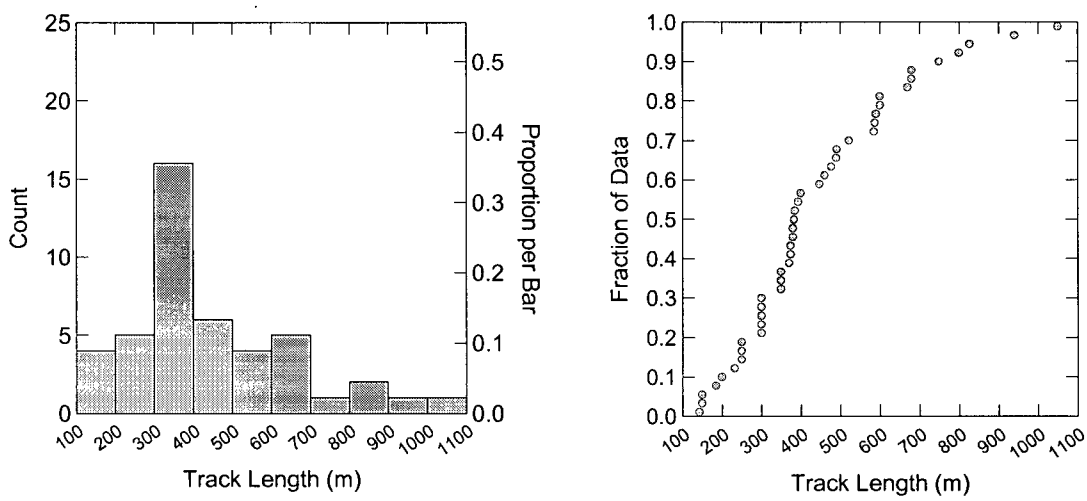


Figure 4.4 Density and Quantile plots of track length for forest penetrating avalanches.

Typically, forest cover is first encountered at or near the top of the track, although in some cases forest cover was not encountered until part-way down the track. For example, one

slide first contacted forest cover in the runout zone on a shallow slope resulting in very little penetration. Approximately 35 % of the tracks are between 300 and 400 m in length, with nearly 89 % less than 700 m along the slope surface. Track length is skewed with a long right tail, the statistic is presented in Table 4.1.

4.2.2 The Runout Zone

Slope Angle

The mean runout zone slope angle is 22°. Paired t-tests show this value to be significantly greater than the mean Type II runout zone slope (t = 3.09, df = 177, Standard error = 0.96 at 95% C.I.) and the same as the Type I average runout zone slope (t = 0.111, df = 131, standard error = 1.18 at 95% C.I.). The distribution is shown in Figure 4.5.

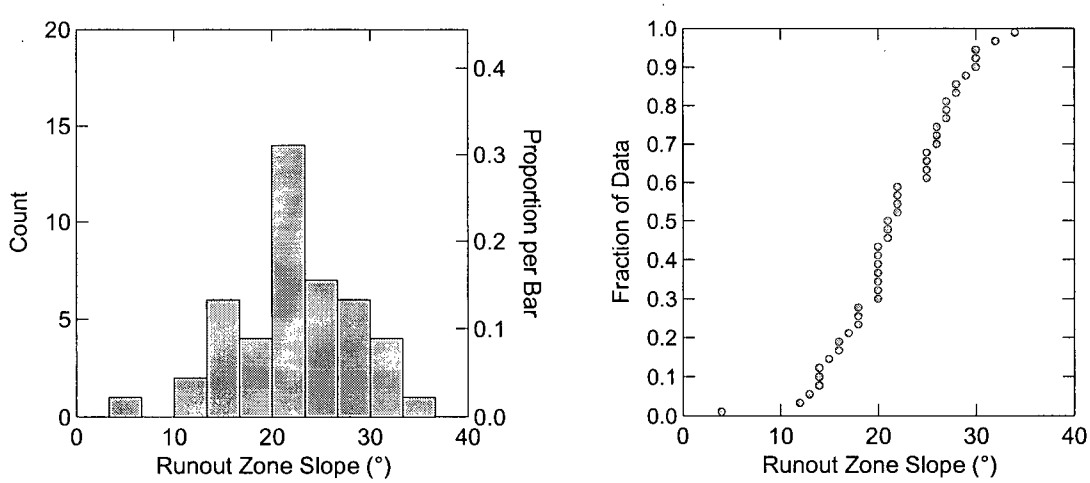


Figure 4.5 Density and Quantile plots of average slope angles measured in the runout zone of forest penetrating avalanches.

The maximum runout zone angle measurement is 34° and the minimum is 4°, the mean is 22°, and the standard deviation is 6°. The slide which stopped on a slope angle of 34° was in the vicinity of 6 other slides in the Nagle Creek example discussed earlier. For the purpose of this study, the seven forest penetrating fingers are considered separate avalanches. All seven

occurred simultaneously and shared a common fracture line, spanning the entire cut-block. It is necessary for this research to estimate the contributing start zone areas and individual track and runout characteristics for each forest penetrating finger in order to determine the physical variables leading to different runout lengths. Slide #7, which terminated on the steepest runout slope, initiated from the smallest (estimated) start zone. The relatively small degree of down-slope funnelling may be the greatest difference between this path and the proximal, longer running paths. The cross slope shape transition is described in Table 4.3. The cross slope shape index value for path 7 is 0, indicating no change between path segments, while the three longest neighbouring paths had positive cross slope shape transition indices, indicating a greater potential for down-slope travel due to funnelling or channelling. The data are approximately normally distributed.

Cross Slope Shape

The runout zone cross slope shape is strongly positively skewed, indicating most of the runout zones are horizontally concave (gullied). Of 45 examples, 2 contain runout zone slope shapes that are horizontally convex. There is no propensity for any positive horizontal slope shape category to be more frequent than another. Figure 4.6 presents the distribution of horizontal slope shapes measured in the runout zone. The skewness most likely represents mountain terrain shape (since the sample is biased toward concave cross slope cut-blocks).

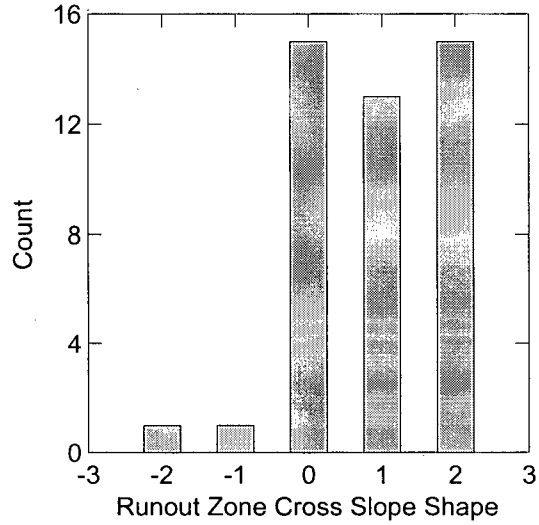


Figure 4.6 Bar chart plot of runout zone cross slope shape for forest penetrating avalanches.

Runout Zone Width

Approximately 96 % of the runout zone widths are 110 m or less with two outlying values at 200 and 250 m wide; 82 % are 90 m wide or less. Figure 4.7 presents the runout zone width distribution.

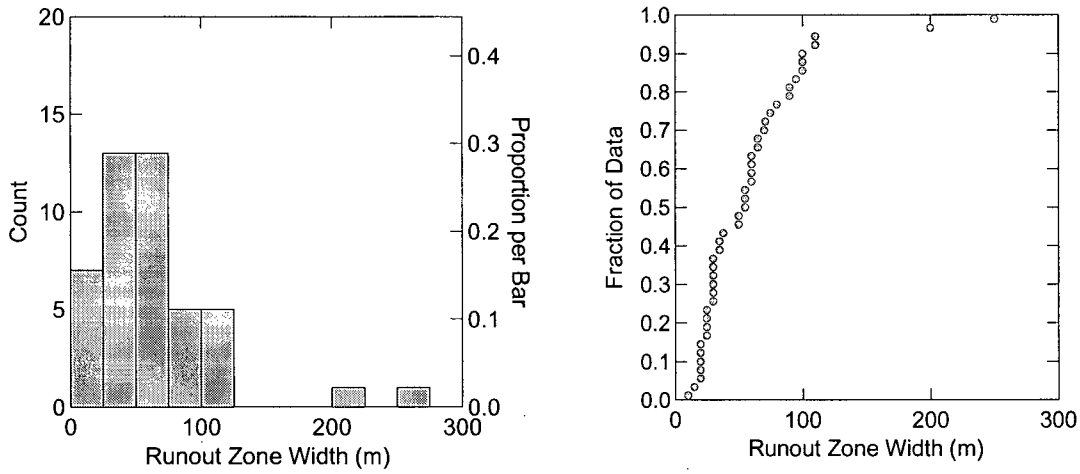


Figure 4.7 Density and Quantile plots of width measurements in the runout zone for forest penetrating avalanches.

Runout Zone Length

The shortest runout length is 50 m, the longest is 720 m; 89 % fall between 100 m and 300 m long. Nearly 50 % fall between 100 m and 200 m in length. Figure 4.8 presents the runout zone length distribution.

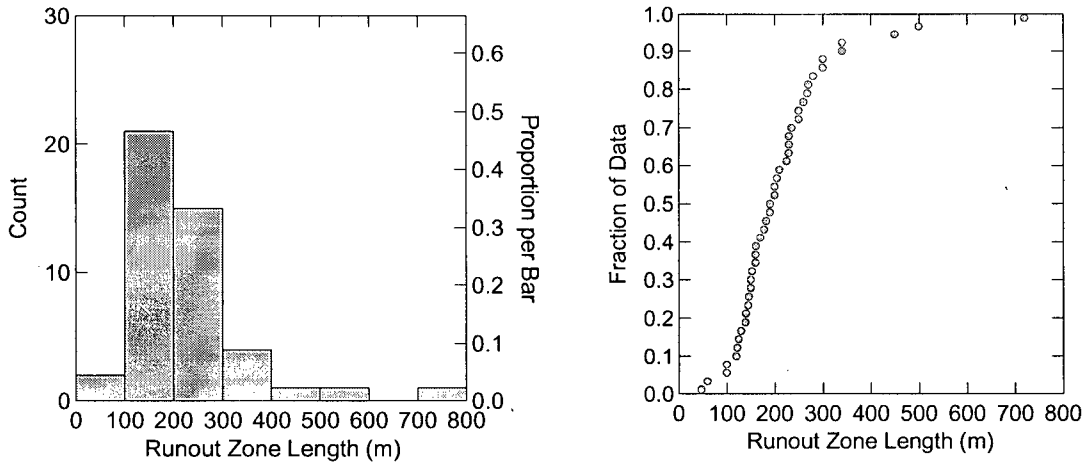


Figure 4.8 Density and Quantile plots of length measurements for forest penetrating avalanche runout zones.

Caution should be employed when using the runout zone parameters because they are not measured relative to a physical terrain shape feature (such as a certain slope angle). The β point analysis utilizes a standard reference point (10°) to circumvent the problem of subjectivity (in human judgement). These runout distances are estimated from the point at which each avalanche began decelerating (usually at a break in slope) to the toe of the deposit or damage. This was judged in the field according to breaks in slope, deposits at the bottom of runout zones, and the first incidence of debris deposited.

Runout Zone Lateral Spread

Figures 4.9 and 4.10 show the relationship between average widths measured in the track compared to average widths measured in the runout zone. The spread relationship is important

when determining the potential risk to structures built at the bottom or near the bottom of potential new avalanche paths. Figure 4.9 shows the spread ratios (runout zone width (m) divided by the track width (m)). The relationship shows how avalanche width behaviour was affected in the runout zone when it decelerated under forest cover. A value less than 1 indicates the width of the avalanche decreased after entering the runout zone. Values equal to 1 indicate the avalanche remained the same width as it decelerated in the runout zone; values greater than 1 indicate a lateral spreading in the runout zone. The greatest width increase in the runout zone was 3 times the width of the track.

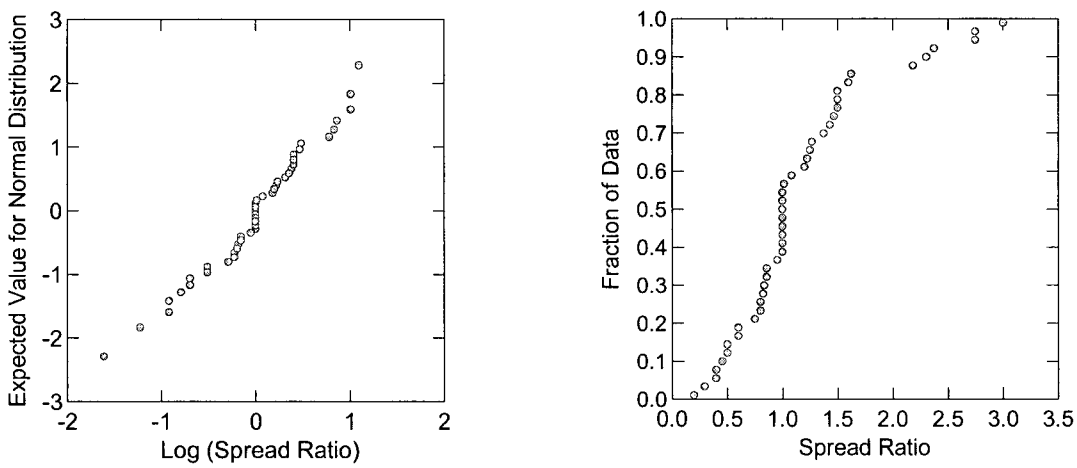


Figure 4.9 Log-normal plot and Quantile plot of the runout zone spread ratio for forest penetrating avalanches.

It should be noted that the distributions represent ratios rather than absolute width measurements. The extreme case descended through a track width of 20 m spreading to a width of 60 m in the runout zone indicating a 20 m lateral spread from each flank of the track into the runout zone. A scale independent ratio such as this is useful for quantifying and understanding the behaviour of the avalanche after entering forest in the runout zone. It is also useful to gain a sense of the actual spread possibility in terms of real distance; this is important for practitioners in the field when it would be useful to visualize the potential spread at the ground level scale.

Down-slope cross slope shape differences (or degrees of confinement) should be considered when assessing the potential for lateral spread. Here, absolute lateral spread is calculated by subtracting the average width of the track (m) from the average width of the runout zone (m). Negative values denote a narrowing of the path; positive values indicate a widening of the path in the runout zone. Figure 4.10 shows the actual runout zone lateral spread measured in metres.

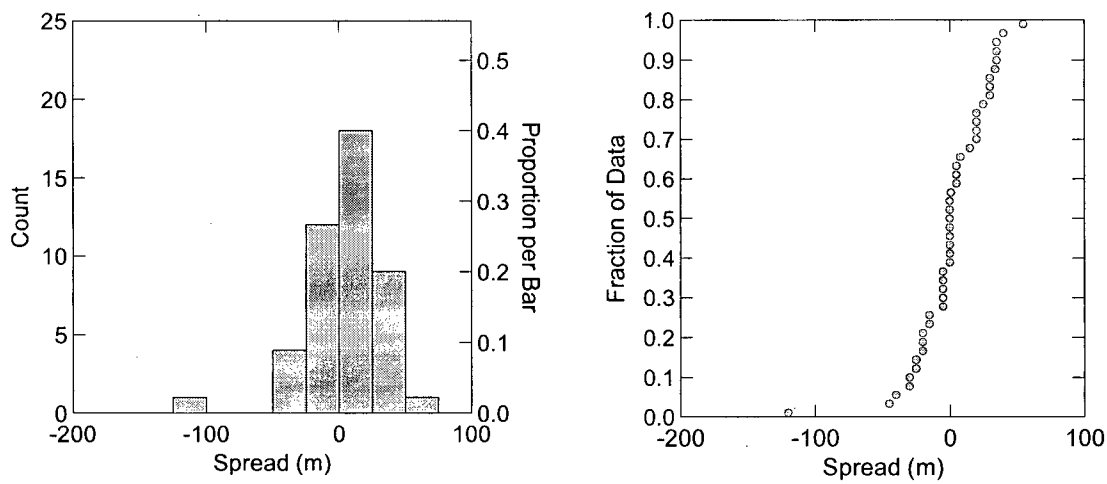


Figure 4.10 Density and Quantile plots of the runout zone spread for forest penetrating avalanches.

Of concern in applications, are avalanches which spread significantly once entering the runout zone. The largest spread is 55 m, spreading 27.5 m laterally from each side of the track as it decelerated in the runout zone. The cross slope shape was category 1 for both the track and runout zone for this case but the slope angle decreased significantly from the track to runout zone. The neighbouring 6 paths averaged a lateral spread of 27 m ranging from 0 m to 40 m. The main physical terrain differences between this path and its neighbours are that it stopped within forest cover, and stopped on a relatively flat slope (14° compared to a 24° average for neighbouring paths).

4.2.3 Forest Penetration Parameters

Damage Areas and Penetration Distances

For the damaged areas, five cases of damage are greater than 3 ha, the rest (89%) are smaller than 3 ha. The mean is 1.7 ha, the largest being 6.3 ha and smallest 0.02 ha in size. The mean path length below penetration distance is 405 m with a minimum of 2 m and a maximum of 1250 m. Figure 4.11 is a quantile plot of damage areas and penetration distances below forest cover.

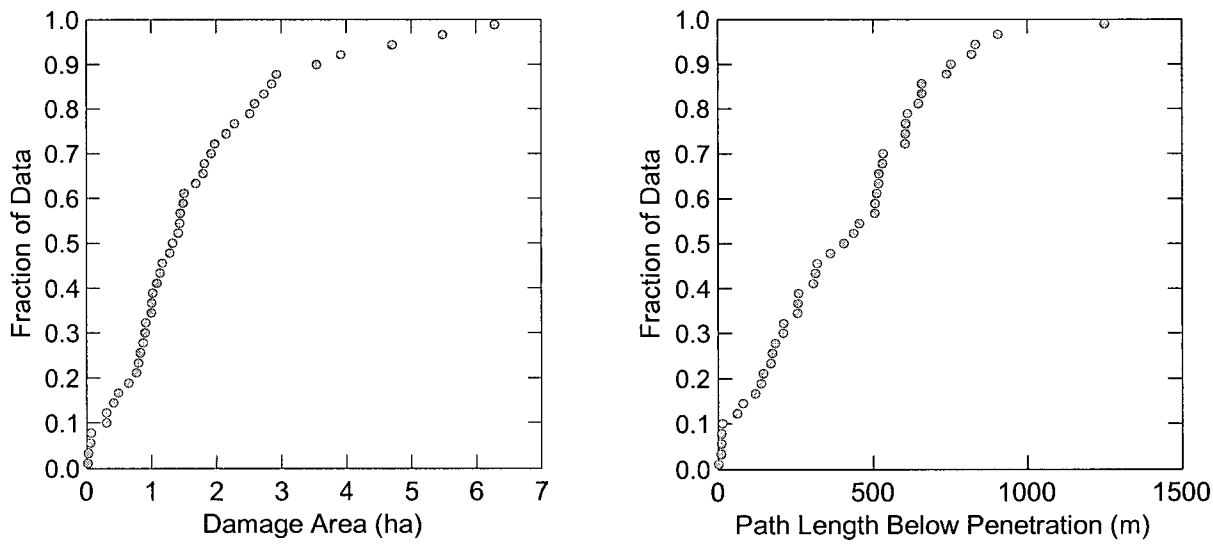
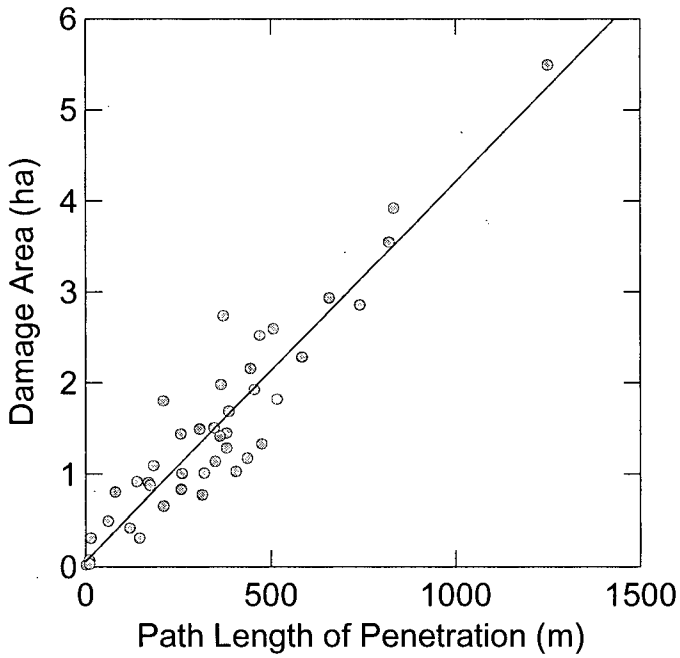


Figure 4.11 Quantile plots of damage areas and forest penetration distances.

Damage areas are roughly rectangular in geometry as shown by the relationship between path length of penetration and damage area. Figure 4.12 shows an approximate linear least squares relationship between damage areas and path length of forest penetration. The relationship indicates that forest penetration is a rectangular phenomenon; the damage area is directly proportional to the length of penetration. In forested runout zones the spread can be significant (refer to Figure 4.10). The probable damage widths of an avalanche in the runout

zone can be roughly estimated if assumptions can be made about confining terrain features in the track and runout zones. Once potential spread in the runout zone is estimated, the area susceptible to damage can also be estimated given the equation Y = 0.039 + 0.0042X, the standard error is 0.20 ha. The constant is negligible and the regression was fit through the origin. One outlying case existed at 6.3 ha damage and is not included in the regression. Path length of penetration for that case was



Regression Statistics:
Y = 0.039 + 0.0042X
R^2 = 0.88
n = 44
Standard Error = 0.20 ha

Figure 4.12 Scatterplot of damage areas vs. path length of penetration.

Crown Closure Class

Figure 4.13 is a bar chart showing the distribution of crown closure class values destroyed by avalanches. Nearly 49% fall into category 6 and 7, showing that half the forested areas destroyed by avalanches were 56-75 % covered by mature vegetation.

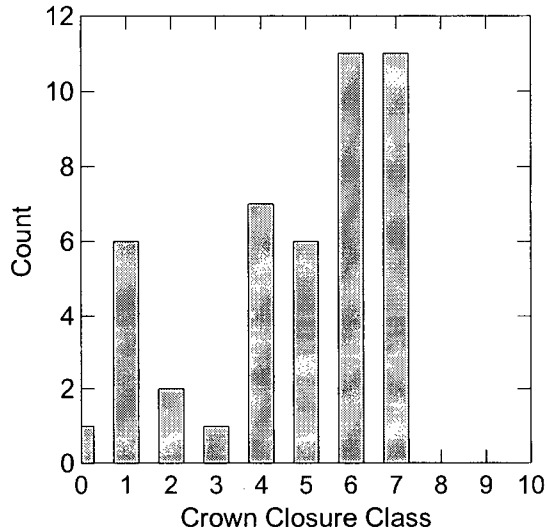


Figure 4.13 Distribution of destroyed vegetation classes according to Crown Closure Class category.

Crown Closure Class (CCC) is the best proxy for tree density available for this study. Quantitative density measurements were not made during site visits other than estimates of high, medium, and low. Better density measurements of forest before it is destroyed are a necessity if density is to be correlated to the distance of forest penetration. It is assumed that highly dense forest would have the capacity to stop an avalanche in a shorter distance than less dense forest. Field experience has shown forest density to vary and, as a result, categories taken from Forest Cover Survey sheets are not always reliable at the scale of one avalanche path; rather they tend to be broadly accurate for larger areas. To have confidence in density estimates, they must be taken prior to the avalanche or, as a last resort, on the slope immediately adjacent to the slide path. However, density measurements taken immediately adjacent to avalanche paths can be misleading since forest cover is commonly less dense in gully bottoms, which is typically the preferred course for an avalanche to travel.

Vegetation Age

The distribution in Figure 4.14 shows 64 % of the age class classifications are categories 8 and 9. This corresponds to ages of 141 years and older. Age categories are broken down in table 4.2.

Table 4.2 Age Class Categories from B.C. Forest Cover Survey Sheets.

Age Class	Age (years)
1	1-20
2	21-40
3	41-60
4	61-80
5	81-100
6	101-120
7	121-140
8	141-250
9	250+

The high proportion of older growth forest showing damage is a function of the nature of this study. Since forest cover was defined with trees at least 5 m in height, damaged trees less than 5 m were eliminated since they do not exert a significant enough influence on the avalanche motion. Typically, timber harvesting is most profitable in areas of old growth forest. These older growth areas are sought after and in most cases the forest left below the cut-blocks is of the same age as timber that was removed from the cut-blocks.

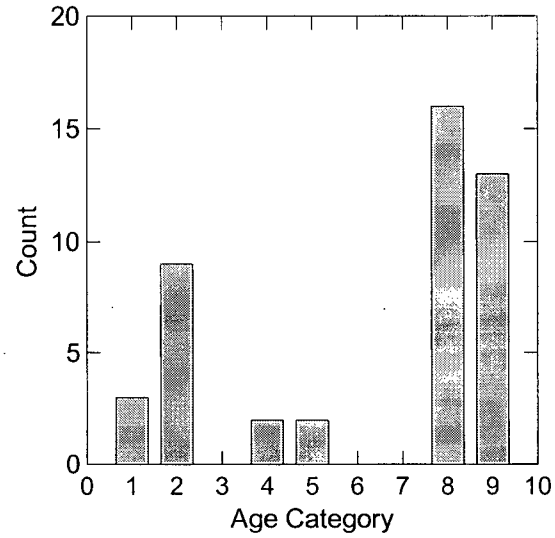


Figure 4.14 Bar chart of forest age classes of forest that was destroyed by avalanches.

Since old growth or highly mature forest cover is often found (and destroyed by avalanches) at the bottom of cut-blocks, the data become skewed indicating a preference for old growth forest to be the most susceptible to damage, when in fact it is not. No conclusions can be made about the susceptibility to avalanche penetration according to the age of vegetation (within the bounds of this study).

Slope Angle at the Forest Penetration Point

The mean slope angle at the forest penetration point is 28°, ranging from 4° to 45° and with a standard deviation of 9.7°. The distribution is shown in Figure 4.15 below.

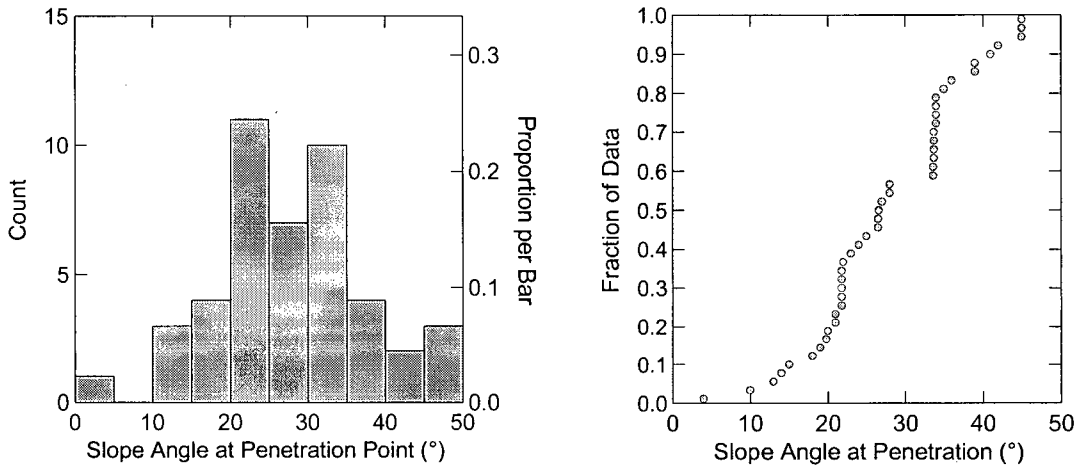


Figure 4.15 Density plot and Quantile plot of slope angles at the point of forest penetration.

4.2.4 Track to Runout Zone Transition

Cross Slope Shape

Cross slope shape differences between the track and runout zone give insight into lateral spread potential according to the physical terrain shape. For example, if a gullied track evolves into a horizontally convex slope as it enters the runout zone, this path would have a high potential for lateral spread. Alternatively, if cross slope convexities or slopes of no cross slope curvature evolve into a gully as it enters the runout zone, a narrowing of the avalanche and a resulting concentration of the avalanche's energy is probable. Avalanches forced into gullies should travel faster than in terrain without curvature since the same volume of snow must pass through a smaller area per unit of time (McClung and Schaerer, 1993).

Here, a cross slope shape transition index for the transition between start zone to track and track to runout zone is developed to attempt prediction of potential runout distances according to the differences in horizontal slope shape or the down-slope progression of 'gullying'. Cross slope shape values have been calculated for each of the three path segments (start zone, track, and runout zone). By subtracting a segment's cross slope shape from the segment below, an indication of the degree of terrain funnelling or expansion is created. Table

4.3 helps to visualise the physical meaning of the cross slope shape values presented in Figure 4.16. The difference value is calculated by subtracting the horizontal slope shape value of the upper segment (in this case the track) from the value for the lower segment (runout zone). The technique can be applied to the start zone to track transition as well as the track to runout zone transition.

Table 4.3 Cross Slope Shape Transition Index Calculation.

Calculation of Cross Slope Shape Transition Index	
Cross Slope Shape Category	**Physical Terrain Shape**
-2	Very Convex
-1	Convex
0	No Curvature
1	Concave
2	Very Concave
Downslope Cross Slope Shape Transition	**Index Value**
Very Concave to Very Convex	-4
Concave to Convex	-2
No Curvature to No Curvature	0
Convex to Concave	2
Very Convex to Very Concave	4

Positive values represent a down-slope horizontal increase in concavity or deepening gullies; negative values indicate a down-slope horizontal increase in convexity. Figure 4.16 shows the difference between horizontal slope shapes for the track to runout zone transition for the TI and TIII data.

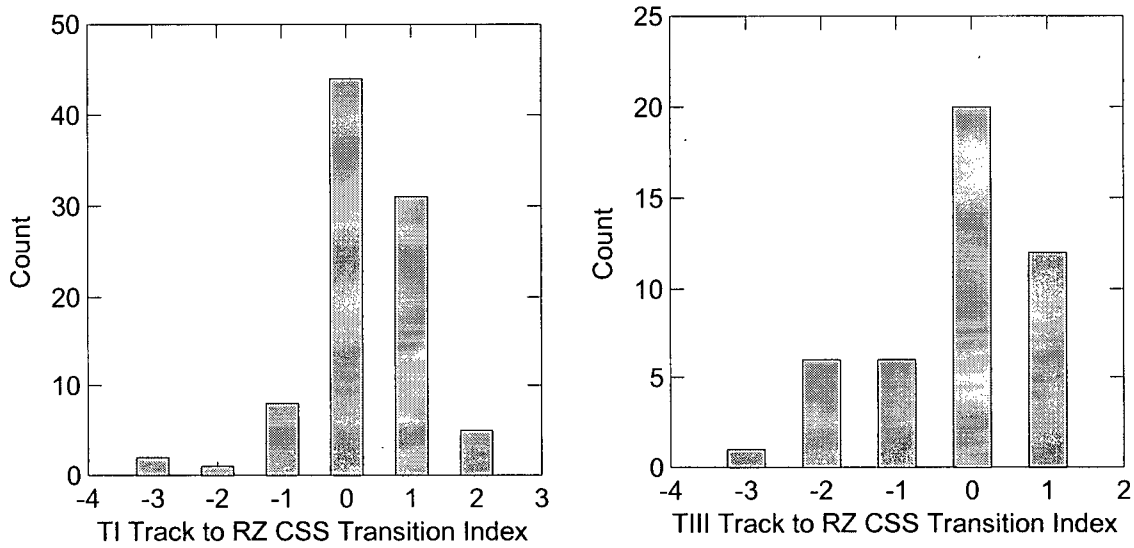


Figure 4.16 Bar Charts of track to runout zone CSS transition index.

Less than one third of the forest penetrating avalanches contain track to runout zone CSS transition values less than 0; the remainder show down-slope planarity or increasing horizontal concavity. If we assume that TIII avalanches contain concentrated (more focussed) energy compared to TI since they were sufficient in energy to penetrate forest cover, it may be reasonable to expect the CSS transition values for the Type III data be significantly higher than those for the Type I data. A two sample t-test reveals this to be false. The TI data have a significantly higher mean than the TIII data for the track to runout zone cross slope shape transition. However, nothing is revealed about the start zone to track transitions. The degree of funnelling between the start zone and track may be of higher importance since it is at that interface that the limit of energy concentrated into the track and runout zone is determined. Figure 4.17 shows the path length below penetration plotted against the start zone to track CSS transition index.

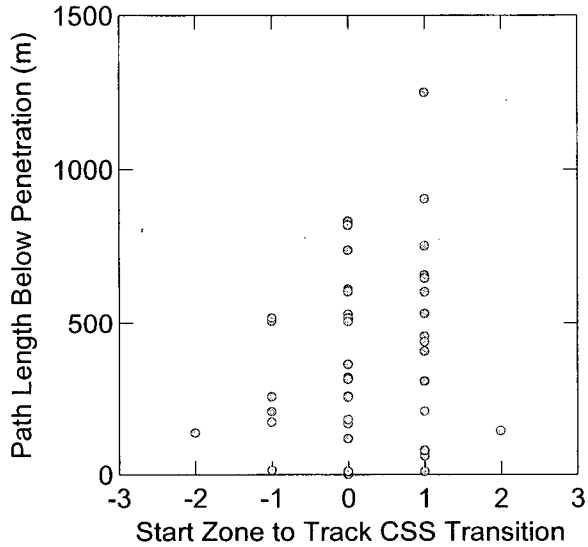


Figure 4.17 Plot of distance travelled below the penetration point vs. start zone to track CSS transition index.

There is no statistical significance to the plot presented in Figure 4.17, and the development of the CSS transition is still in its infancy stages. The purpose for its inclusion here is to call attention to a potential relationship between the degree of funnelling and the potential runout distance. The highest CSS transition values correspond to the greatest range of down-slope penetration. This shows that terrain shape indicates the potential for avalanches with greater start zone to track funnelling to produce longer running avalanches than those of lesser funnelling. The idea here is that the more concave the terrain becomes as the avalanche travels down-slope, the farther the avalanche could travel. This relationship has been observed in the field but for the CSS transition to be of use a scaling parameter should be developed (such as start zone width or other measure of terrain scale).

4.2.5 Other Descriptive Statistics

Start Zone Slope Angles

Most of the avalanches initiated on slopes between 30° and 40°, which is a typical range reported many times by many different researchers (e.g. McClung, 2001 for TI data). The distribution is presented below in Figure 4.18.

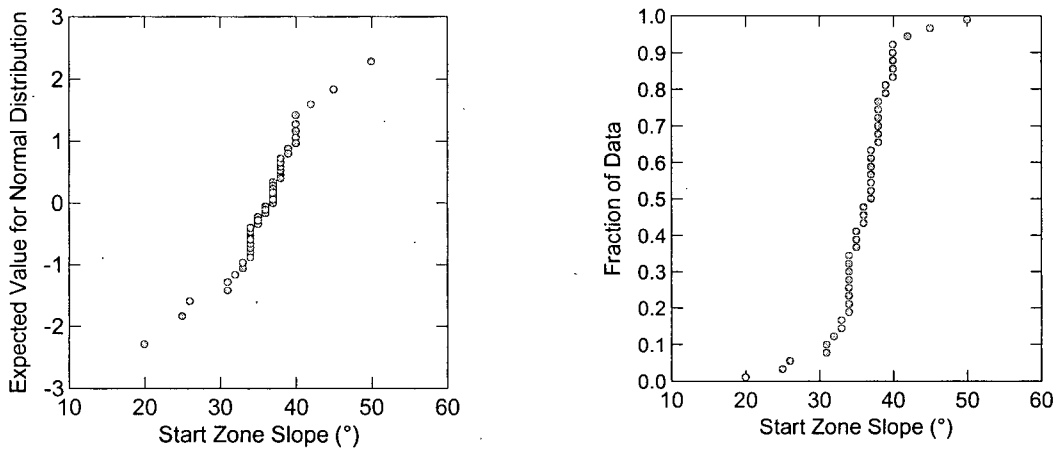


Figure 4.18 Probability plot and Quantile plot of start zone slope angles.

Avalanche Size

Nearly 70 % of forest penetrating avalanches were estimated to be size 3 and 3.5 according to the Canadian Size Classification Scheme (Chapter 1). There are no size 5 avalanches and the smallest was a size 2.5. Figure 4.19 shows the Type III avalanche size distribution.

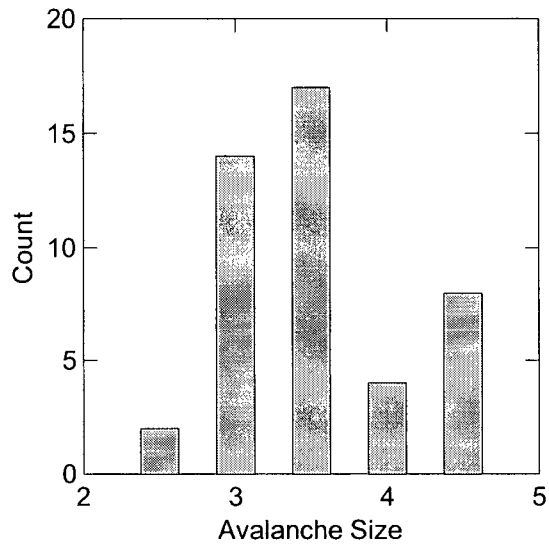


Figure 4.19 Bar chart of avalanche size distribution for forest penetrating avalanches according to the Canadian Avalanche Size Classification Scheme.

The lack of size 5 avalanches is logical considering the database is biased towards Type I avalanches. Of 91 Type I avalanches initiating within logging cut-blocks there were 0 size 5 avalanches (Stitzinger, 2001). This is a reasonable indication that some caution is being taken when cut-blocks are sited, since creating potential size 5 avalanche producing terrain is an unacceptable level of risk (Weir, 2002). Creating potential size 4 avalanche terrain is unacceptable for Canadian risk managers. Type II avalanche paths have the potential for larger magnitude avalanches because the start zones are not bound by the size of a cut-block. There are 7 Type II avalanche paths contained in the forest penetration database comprising 16 % of the database; the largest of these is size 4.5.

The smallest case was a size 2.5 avalanche. It is not surprising that the smallest avalanche to have an impact on forest cover was size 2.5 given that the definition of a size 3 avalanche is the smallest that could break trees according to the Canadian Avalanche Size Classification Scheme (and that estimation of size is a somewhat subjective estimate in a field

setting). Only one avalanche is classified as size 2.5; it penetrated forest that was situated in a creek bed and was characterized by low forest density. It is also possible that the magnitude of this avalanche was underestimated during the original field visit.

Total Vertical Fall

The total vertical fall gives a real sense of the overall range of avalanche sizes contained in the Type III database. The mean value is 492 m elevation, ranging from 190 m to 871 m. Figure 4.20 shows that approximately 70 % descended less than 550 m.

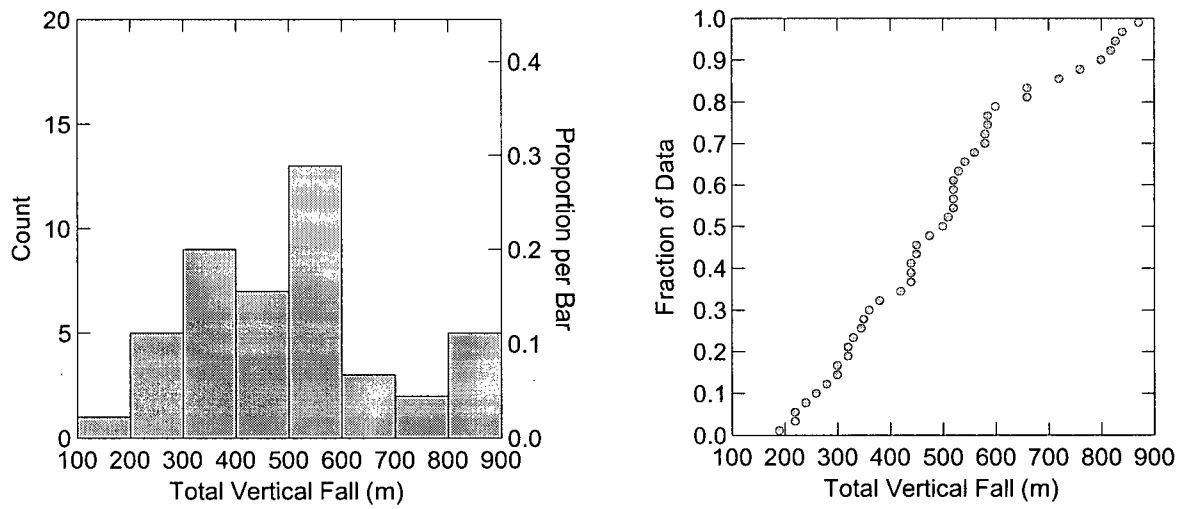


Figure 4.20 Total vertical fall for avalanche paths penetrating through forest cover.

Aspect

Aspect was grouped into 8 categories, each spanning 45°. Roughly 56 % of all the forest penetrating avalanches fall within categories 1 and 2 (0-90° Azimuth). Figure 4.21 shows the distribution of Aspect measurements for 45 forest penetrating avalanches.

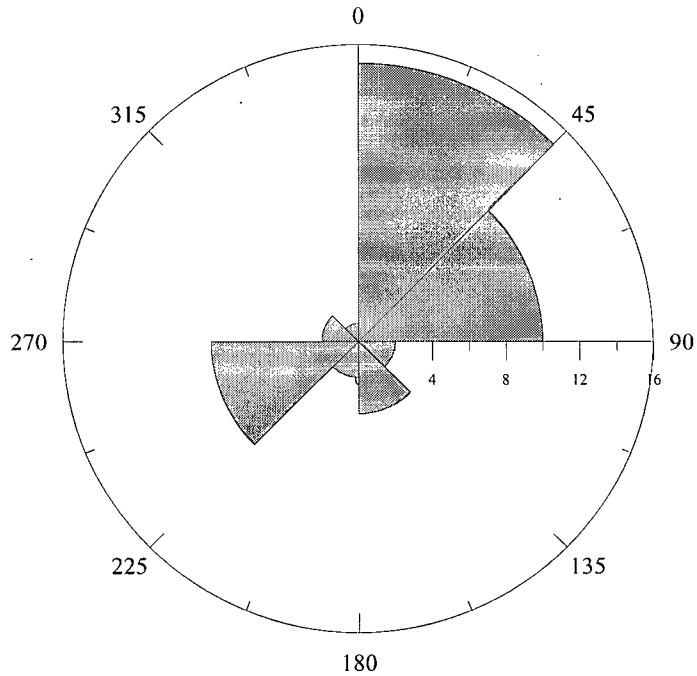


Figure 4.21 Frequency of forest penetrating avalanches according to aspect category.

Readers should be cautious in drawing conclusions about the relatively high proportion of destructive avalanches initiating on a north-easterly facing aspect. The two case examples described in Chapter 1 (Nagle Creek and North Blue River) are comprised of 7 and 5 avalanche paths respectively, and the aspect of each of these paths falls into categories 1 and 2. Since the Type III database is relatively small, these two events skew the distribution towards aspects 1 and 2. The categories were arbitrarily chosen and do not reflect any physical terrain characteristics. Only longer term monitoring of newly created avalanche paths on all aspects could be used to determine whether there is a propensity for forest to be destroyed on north-east facing aspects or whether it is a characteristic of mountain terrain.

4.2.6 Alpha and Beta Angles

Alpha Angles

The mean Alpha angle is significantly higher than the mean beta angle (paired sample t-test, p = 0.001), indicating avalanche termination points occur up-slope of the beta point for these forest penetrating avalanches. Below, in Figure 4.22, the alpha angle distribution is presented.

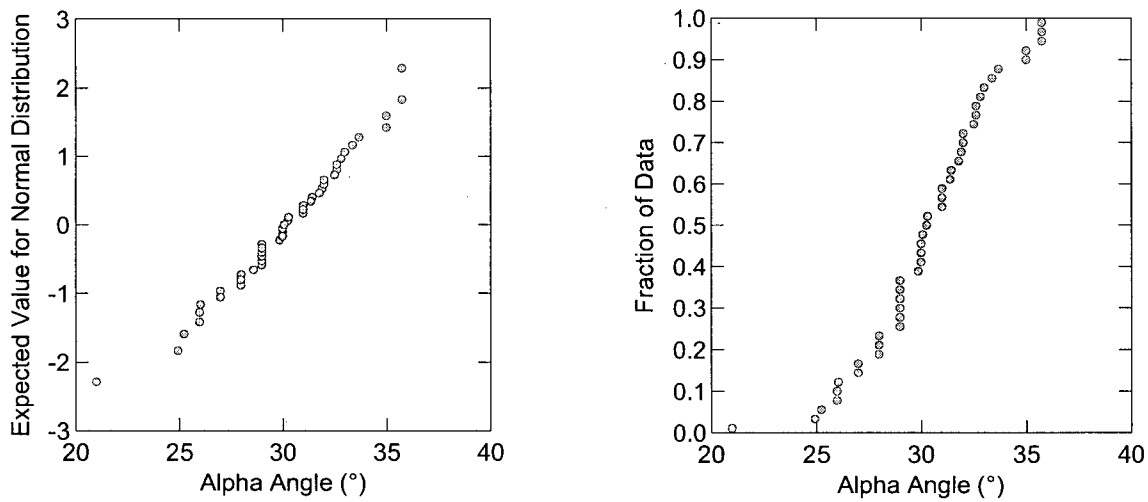


Figure 4.22 Probability plot (left) and Quantile plot of alpha (α) angles.

The mean alpha angle is 30°, ranging from 21° to 36°; 76 % fall between 29° and 36°. There is one 21° outlying case, identifiable in Figure 4.22. The Ministry of Transportation and Highways in B.C. (MOTH), uses 25° as the upper 'safe' limit for situating roads with acceptable level of risk to users (described in Chapter 1). The quantile plot above shows the 25° value to be useful to protect highway users since only one of 45 cases ran below 25°. This case ran through very low density forest cover and into a clear-cut below the forest. It was stopped by relatively dense forest at the lower boundary of the cut-block. In practice, when there is a significant leave strip of forest between a highway and possible start zones, it is common to assume a greater degree of safety than if there were no forest cover present.

The quantile plot shows this to be a valid assumption since only a few avalanches ran through forest cover and stopped close to a 25° α. However, in spite of the presence of forest in the track and runout zones, avalanches can still reach the 25° point. When avalanche assessments are being conducted for new cut-blocks, there is no 'rule of thumb' with respect to increased safety through protective forest to determine the highway/feature to be within an acceptable level of safety, even if α is less than 25°. However, the data suggest that the presence of forest cover does reduce runout distances. For assessments on potential borderline 25° α runout terrain, forest cover may be considered to increase the safety of features below the 25° point and even upslope of that point as shown in Figure 4.22.

Beta Angles

The average β angle for these data is 29° with a standard deviation of 3°. The lowest beta angle is 20° and the highest is 35°. Figure 4.23 shows the distribution of beta angles. The runout toe position for 44 of the 45 paths is at or above the β point, only one avalanche reached and descended beyond the β point. In this case, forest cover was not penetrated until below the beta point. In all other cases (that did not reach the beta point) forest cover was encountered up-slope of the beta point. The retarding potential of forest cover is exemplified in the runout toe positions. It is common and standard practice to expect avalanches to travel past a 10° β point. Here it is shown that those avalanches which encountered forest cover upslope of the β point were influenced by the presence of forest and did not travel beyond the β point. The quantile plot of the β angles shows data measured from slope profiles calculated in the GIS.

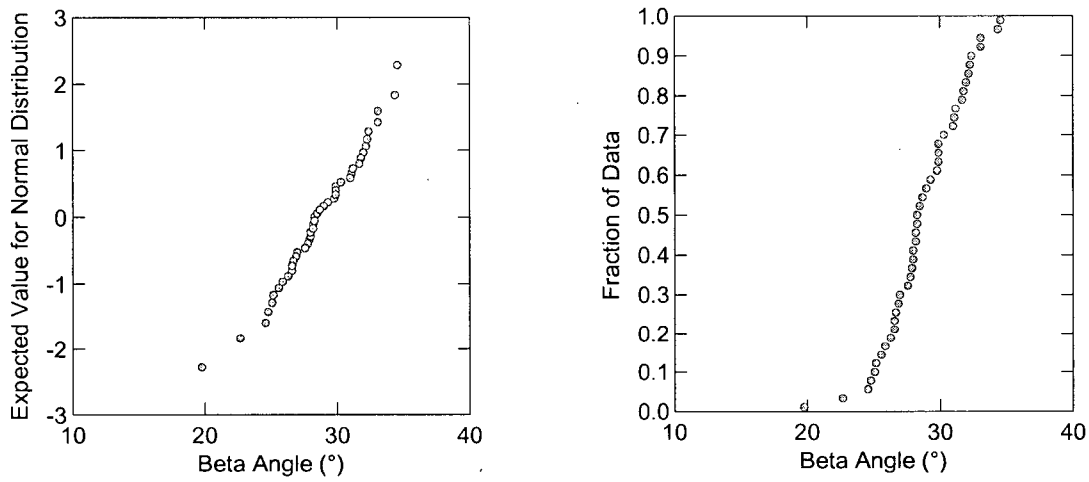


Figure 4.23 Probability plot (left) and Quantile plot of β angles for forest penetrating avalanches.

The event which descended beyond the beta point has a relatively high 30° beta angle and an alpha angle of 29°. The beta angles are approximately normally distributed with two outliers below 25°.

4.2.7 Runout Ratios

Runout ratios were first calculated using points of forest entry as the reference point; this is the point where the avalanches first enter mature forest cover below the cut-blocks. For these runout ratios, X_F becomes the horizontal distance from the top of the start zone to the point of forest entry and Δf is the horizontal distance travelled from the point of forest entry to the bottom of the runout zone. Once the ratios were calculated, they were fit to Gumbel and Weibull distributions. It was found that conventional runout ratios presented for short slopes in Jones (2002) may fit better to a Weibull distribution rather than a Gumbel distribution (McClung, pers comm., 2004). Here, a Gumbel distribution and a Weibull distribution were developed for the forest entry point runout ratios ($\Delta f/X_F$), but neither provided a good enough fit for practical use.

A difficulty in this approach is that the forest cover exists on the slopes at different reference points for different cases; for example, the first encounter of forest doesn't always

occur at 10°. The theory behind developing runout ratios for the point of forest entry is that the farther the avalanche descends before hitting forest cover, the farther it should penetrate. One problem is that in some cases there was sufficient density and available distance of forest cover for the avalanche to dispense all of its energy and stop under the cover of forest. For other cases in which there were shorter protective leave strips, avalanches travelled completely through the leave strips into open, non-forested slope below the forest. Other physical terrain features may have a greater impact on the behaviour of the avalanche than forest cover. In some cases large bench features had a greater retarding effect on the avalanche than the forest cover itself.

Beta point runout ratios were calculated for a 10° β point as well as the forest penetration point. Some researchers have used higher angle beta points (Jones, 2002), but the most commonly used definition and therefore the best for comparison purposes is a 10° beta point. Mean runout ratio values are compared to mean values reported by other researchers. Table 4.4 shows the α, β, δ, vertical fall (H), and $\Delta x/X_\beta$ values for the Canadian Rockies, Coastal Alaska, B.C. Coast Range, Columbia Mountains, Short Slope Dataset, Norway, Colorado, Sierra Nevada, and Iceland compared to the Type III dataset. In Table 4.4, the forest penetrating avalanche dataset is the only one which exhibits higher α angles than β angles and is the only data exhibiting a negative mean runout ratio.

It should be noted that the TIII δ angle values represent the angle between the β point and runout position, for all except one case, this exists above the β point. All other datasets contain lower α angles than β angles and therefore represent the traditional interpretation of the δ angle (refer to Figure 1.2).

Table 4.4 Mean Runout Ratios and Runout Statistics (adapted from McClung and Mears, 1991, and Jones, 2002 (for short slope data)).

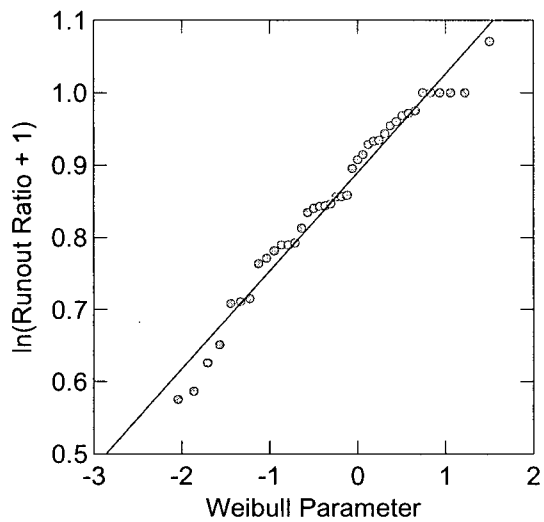
Value (Mean)	Forest Penetrating (TIII) N=45	Columbia Mountains N=46	Canadian Rockies N=127	Coastal Alaska N=52	B.C. Coast Range N=31	Western Norway N=127	Colorado Rockies N=130	Sierra Nevada N=90	Short Slopes N=46
α (°)	30.3	32.5	27.8	25.4	26.8	29.4	22.1	20.1	26.5
β (°)	28.7	34.2	29.8	29.6	29.5	32.6	27.5	26.3	27.5
δ (°)	18.2*	7.9	5.5	5.2	5.5	6.4	5.1	4.8	10.1
H(m)	492	538	869	765	903	255	543	429	224
$\Delta x/X_\beta$	-0.20	0.06	0.11	0.25	0.16	0.18	0.41	0.49	0.05

* The TIII δ angles are not true to the standard definition of the δ angle. Since the forest penetrating avalanches terminate upslope of the β point, the δ angle represents the angle between the β point and the runout position. It is sighted upslope from the β point to the runout tip.

There are a number of important points to consider when examining these data. The data show that all but one of the TIII slides terminated upslope of the β point. This is indicated by the negative runout ratio showing the average runout position to exist significantly upslope in comparison to other datasets. The 10° point has been defined as the point on the slope where extreme avalanches first begin to decelerate (arguments contrary to this have been made). The TIII data indicate there is a retarding effect created by the presence of the forest cover since only one of 45 forest penetrating avalanches reached the 10° β point. The forest cover is in fact providing some protection to down-slope terrain. The α angles also indicate the same effect of forest cover with the average α being higher than the average β for TIII data. All other datasets, without forest cover in the track or runout zone, contain lower α angles than β angles.

The next step toward determining the likelihood of both an avalanche reaching a given point, and the risk at that point is to use a probability analysis. In Figure 4.24 a Weibull probability distribution is presented; the likelihood of an avalanche running through forest cover and reaching any given point on a slope relative to the β point is shown. A description of how

the Weibull parameter is calculated is presented after the figure. A number of assumptions are necessary to understand this technique. It is assumed that the scale of the terrain is large enough and the snow supply is great enough that a size 2.5 avalanche could be initiated. It is assumed that there is forest cover at least 5m in height below a non-forested start zone, and the forest cover exists between the 10° β point and the start zone.



Least Squares:
$Y = 0.17X - 0.12$
$R^2 = 0.94$

Figure 4.24 Weibull distribution for Type III runout ratios

The Weibull distribution is based on the non-exceedance probability, or the probability that a value will not exceed Y. The Weibull parameter is calculated by ranking the runout ratios from highest to lowest, and using the ranks, i, in equation 4.1,

$$\text{Weibull Parameter} = \ln[-\ln(1-(i-0.5)/(n))] \qquad 4.1$$

where i is the case number and n is the number of cases. The vertical axis is calculated by taking the log of the positive runout ratio values (RR +1) since the Weibull distribution can only be applied to positive data. The scale parameter is 0.9, and the shape parameter has a long left tail (Weibull modulus = 6); the coefficient of variation of the Runout Ratio +1 is 0.25.

Some question has been raised as to the validity of the Weibull distribution for the runout ratio data since the sample is not a randomly drawn one. The analysis was run on the dataset with a number of paths excluded to assess whether the data were influenced by these particular paths. The analysis was re-run excluding all but 1 Nagle Creek avalanche and 1 North Blue River avalanche. These paths were excluded since their characteristics are similar to each other and may have influenced the results. When the data were retested and distributed, the regression equations were virtually the same.

The Weibull distribution can be used by practitioners to determine the probability that an avalanche will reach a given point on a slope if there is forest cover between the start zone and point of interest. A runout ratio should be calculated for the point of interest and compared to the Weibull distribution to determine the probability of an avalanche reaching that point, given it penetrated through mature forest cover.

4.3 Assessing the Forest Penetration Potential of New Avalanche Terrain

The first step is to examine the physical terrain in the start zone and track to determine whether or not a significant avalanche is likely to initiate out of the cut-block in question. Use Table 4.5 developed by Stitzinger (2002) to ascertain the risk of avalanche initiation of size 3 or greater from a cut-block.

Table 4.5 Table to determine the risk that a cut-block will produce an avalanche of size 3 or greater. (Reproduced with permission from Stitzinger, 2001).
H=High, M=Moderate, L=Low

Variable		Weighted Categories	Weight	Rank	Score = Rank x Weighted Score
Scale factors	Length	H > 400m M= 200 to 400m L < 200m	6 3 1	5	

	Width	H > 200m M=100 to 200m L < 100m	6 3 1	4	
Start zone cross slope shape		H = 2 M = 1 L = 0	6 3 1	2	
Track cross slope shape		H = 2 M = 1 L = 0	6 3 1	1	
Density of residual vegetation > 1m (Stems per ha)		H ≤ 100 M = 200 to 1000 L > 1000	6 3 1	3	
Scores summed =					
Ranges 0 - 40 = L 41 - 57 = M 58 - 90 = H					

Once the potential for an avalanche of size three or greater to be produced by the cut-block has been established, if that risk is greater than an acceptable threshold, then the potential distance it could penetrate through forest cover below the cut-block should be calculated. This second step provides a magnitude estimate as a function of position on the slope. The distribution of α angles (Figure 4.22) and the Weibull plot of runout ratios (Figure 4.24) for forest penetrating avalanches should be consulted to accomplish this step. The α angle analysis allows the slope to be assessed from a potential runout position. Using the runout ratio Weibull distribution, the probability for an avalanche to reach a potential runout position relative to a 10° β point can be calculated given that there is forest cover in the track and/or runout zone. The use

of both techniques provides the greatest confidence for accurate prediction of potential runout distances for avalanches penetrating through forest cover.

The third step to quantify the risk, often of equal importance, is to assess the potential for an avalanche to spread in the runout zone as it decelerates. An estimate of spread in the runout zone, also based on probabilities, can be made using the distribution of runout zone spread ratios (Figure 4.9). The spread ratios should be used to determine the likelihood that an avalanche will spread to X position on a slope relative to the centre of the avalanche (typically the fall line).

Some attention should be paid to the cross slope shape transition from the start zone to the track. Although a statistically significant relationship could not be established between the degree of funnelling (CSS transition) and penetration potential, it was observed in the field that the avalanches which penetrated farthest through forest cover also exhibited the greatest degree of funnelling. The degree of funnelling can be assessed by examining the difference in slope curvature between the start zone and track. One issue still to be resolved is the development of a scaling parameter for the CSS transition. A scaling parameter will address the issue of small start zones not having the potential to produce avalanches with as great a magnitude as larger start zones.

The three steps outlined above are a method to quantify the risk according to terrain and distance measurements providing a spatial quantification of risk. The risk can be quantified numerically in the form of a probability. This method of quantifying the risk addresses the problem of future avalanche susceptibility (the creation of potential avalanche terrain and the potential magnitude), as well as the issue of public and worker safety for forestry applications.

4.4 Conclusion

The analysis has shown that forest penetrating avalanches are influenced by the forest they penetrate and the terrain shape over which they penetrate the forest. Forest penetrating

avalanches tend to stop relatively up-slope in comparison to avalanches not travelling through forest. Forest cover can be used to protect down-slope resources but terrain characteristics must also be carefully considered. It is primarily the avalanche size and terrain scale in combination with terrain shape which determines whether or not an avalanche will penetrate into forest cover either at the lower boundary of logging cut-blocks, or in or in other circumstances where new start zones are created above mature forest.

Chapter 5: Conclusions

5.1 Review

Avalanche terrain is being created on steep slopes in British Columbia as timber harvesting companies harvest at high elevations due to a decreasing supply of mature timber in valley bottoms. To date, the protective nature of forest cover leave strips has not been quantitatively established; the research presented here is the first attempt to quantify and develop prediction techniques for potential forest penetrating avalanches. The approach is based on terrain and vegetation characteristics rather than climate variables or snow conditions. A number of general and specific conclusions can be drawn from this research and applied to avalanche forest penetration problems as well as more general terrain analysis problems. The following discussion describes the utility of the results that were presented here and the limits for their use in practice.

5.2 General Conclusions

5.2.1 Ground Truthing

Using 1:20 000 scale maps and a GIS program can be enormously effective at increasing the efficiency of research in a study such as this. The technology must be used with caution since it can be easy to forget the limits posed by resolution and the bounds of what is realistic to measure in a GIS and what must be measured or confirmed on the ground. It is reasonable to measure distances, slope angles and large scale features in a GIS but, some features such as gullies are often not visible on 1:20 000 maps. Even on 1:5 000 scale maps these features are not always apparent enough to make any valid measurements without a site visit.

5.2.2 Return Period

The return period for avalanches initiating in logging cut-blocks was initially estimated to be approximately 1 event in 10 years (Stitzinger, 2002). Now, there are more years of record, and, for most of the cut-blocks used in this study the return period appears to be closer to 1 in 5 years. Data were not collected in this study to verify this fact. However, through discussion with practitioners it has become apparent that most of the cut-blocks have produced avalanches at a higher frequency than 1 in 10 years. Some sites are thought to produce avalanches greater than size 2 on an annual basis, avalanches have recurred at Nagle Creek since the initial forest destroying one.

5.2.3 Continuing Database Development

An important fact that has emerged through this work is that there is not yet enough information and this database should continue to be built. Forest destroying avalanches occur every year and it would be relatively easy to build the database as they happen. The main reason this would be desirable is that once enough data are collected for avalanches that have penetrated through forest cover leave strips as well as those which stopped within forest cover (where the forest cover extends to the valley bottom) a more thorough analysis could be conducted. It is important to look at these two situations as two different types of damage, currently there are not enough data for the Type III database to be divided into these two groups.

5.3 Forest Penetration Conclusions

5.3.1 General Problems

The analysis in this study developed strategies to predict potential avalanche runout distances through forest cover and potential lateral spread as avalanches decelerate under forest

cover in the runout zone. For penetration distances a number of important variables emerged. The data used in the study are quite varied and cases differ significantly in their terrain and vegetation characteristics. While some terrain characteristics are relatively simple to quantify (distances, slope angles) and to measure, other variables are not as simple to measure or quantify. The density and extent of forest damage are not straight forward to determine from photos and in some cases the values used were 'best estimates'. For sites which were visited before the development of the TIII database, it was sometimes difficult to determine the exact point of forest entry since the data collected at the time did not include such a description. For some of these sites it was difficult to determine the necessary values from airphotos or site photos if the photos were taken either before, or after the forest destroying avalanche event. Since both before and after photos were not always available, best guess estimates had to be made from field notes, terrain characteristics, debris deposit locations, and the interpretation of available photos.

A second problem occurs with the timing of the photographs. For some cases the damage was not noticed until years after the forest destroying event or events, or if it had been noticed there were no photographs taken at the time of the event. A new unknown is introduced by this fact, it is unknown whether the forest destruction came as a result of one avalanche or whether it was the result of a number of successive avalanches which progressively destroyed forest further down-slope with each event. The Blue River example presented in Chapter 1 is a good example of a case where this did happen. The Avalanche Research Group visited the site in the summer of 2000 for a small slide that descended down a gully at the North end of the cut-block, destroying a small amount of forest as it ran through the gully. It is unknown whether the entire cut-block slide at that time and most of the slide was stopped by the leave strip at the bottom of the block, or if it was a small event which only initiated above the gully in question. In 2003, a (probably) larger event produced the avalanches shown in the North Blue River figures in

Chapter 1, creating 5 forest destroying avalanches. In this case it is known that there were at least 2 events, a small one which did not penetrate forest on a large scale and a large on which produced a significant amount of damage. Nagle Creek has also experienced significant avalanches since the large event that penetrated through 7 lobes of forest cover. It is unknown whether the repeat events travelled further than the initial forest destroying avalanche.

A third source of error is the difference in available penetrable forest below the cut-blocks. Initially, avalanches stopped by a road, river bed, or the bottom of a valley were not included in the database since these terrain features clearly had an influence on the avalanches' behaviour in spite of forest cover having been destroyed. Nearly half of the slides ran through the forest leave strips descending into non-forested or newly replanted slopes below the leave strips. The remainder of the slides ran into and were stopped under mature forest cover by the forest itself or physical terrain features. The problem arises since the avalanches runout in two types of conditions: forested and non-forested slopes. It is unreasonable to divide the database into the two types since no reliable results can be concluded from such a small sample.

5.3.2 Runout Penetration Distance Prediction

Since the characteristics of the paths analyzed are so greatly varied, the Weibull distribution of runout ratios should be used cautiously in determining potential runout distances. The distribution applies to any potential avalanche path which contains forest cover between the starting zone and a point of interest on the slope below. It is based on paths which contain many different terrain and vegetation characteristics. The Weibull analysis was conducted on a non-random, censored data sample since the paths were initially selected from a larger dataset and some had penetrated completely through forest leave strips while others stopped under the cover of forest. The distribution does not represent the probability that any avalanche will penetrate to

a given distance through forest cover. The plot represents the likelihood that an avalanche will reach a point down-slope given that it is at least a magnitude of size 3.

5.3.3 Lateral Spread in the Runout Zone

Lateral spread in the runout zone is less variable than penetration potential and depends on confining terrain features. Runout zone widths are confined according to the cross slope shape, regardless of whether or not there is forest cover in the runout zone. Field observations indicate the presence of forest cover in the track may augment the damage widths by extending the width of the slides. However in the runout zone the presence of forest cover does not significantly alter the avalanche width behaviour since it is mostly defined by the cross slope shape in the runout zone. Terrain shape is likely to be more important than vegetation in influencing the runout zone widths, unless the slope is without cross slope curvature. The probability of forest penetrating avalanches spreading to X point on a slope lateral to the avalanche runout zone can be calculated using Figure 4.9.

5.4 Future Research

5.4.1 Ongoing Monitoring

The TIII database as it exists is not large enough to separate avalanches into similar enough characteristics to provide results specific to cases. For example, cases for which forest leave strips exist in potential runout zones between two cut-blocks are different than those which contain consistent forest cover to the valley bottom. It is important to continue the database development to gain a better knowledge on return periods, and to develop even better techniques to predict forest penetration distances for avalanches running into narrow as well as wide forest leave strips.

5.4.2 Forest Fire/Avalanche Terrain Interaction

The summers of 2003 and 2004 produced particularly destructive fire seasons, where vast areas of forested land were burnt, destroying the forest stands and their protective function to avalanche initiation. Burnt forest, if still standing, is weakened and may provide reduced protection against avalanche initiation and penetration into down-slope forest or other resources. It would be useful to design a study to examine the effects that a burnt-out forest would have on avalanche behaviour. If large areas of land in avalanche terrain contain burnt timber, the potential for large post-avalanche debris deposits is high, with a high likelihood of creeks and rivers becoming dammed when the burnt forest is transported to valley bottoms.

5.4.3 Cross Slope Shape Transition

The CSS transition index presented in this thesis is a first step at developing a scaled funnelling index. The index will be used to describe the degree of funnelling over distance of avalanche producing terrain in logging areas. A funnelling index is a proxy for the degree of energy concentration as snow becomes confined while avalanches descend.

At present the cross slope shape transition index is based entirely on cross slope shape and no significant relationship has been found between the degree of funnelling and the distance of penetration. Field observations indicate that the farthest penetrating avalanches occur on slopes that progress from no or slight cross slope concavity to high cross slope concavity. Thus far this relationship has net been statistically proven. For a cross slope transition technique to become of use it will be necessary to develop a scaling technique so that some measure of start zone area or width/length (potential magnitude) are included in the prediction.

5.5 Final Words

The presence of forest cover does provide protection from avalanches descending out of cut-blocks, this is indicated by the α angle normal distribution and the runout ratio Weibull distribution. However, terrain shape characteristics also have a significant influence on avalanche behaviour. The results of this work can be used to predict the likelihood that an avalanche will descend through forest cover to a given position on a slope. The probabilities can be calculated and used to determine the risk at a position on a slope if forest cover exists between that position and a potential start zone. The tools presented here are meant to be used as aids to field practitioners who assess what risk cut-blocks may pose to down-slope features. The tools are not substitutes for expert knowledge and experience, but should be used in combination with those skills. The techniques presented in this work are the first to approach the forest penetration problem quantitatively. The first quantitative methods to evaluate the forest penetration problem have been developed, and they can now be used as components of field assessments when avalanche risk to features or people down-slope of forest cover is being evaluated.

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