INVENTORY OF FOREST LANDSLIDE OCCURRENCES IN THE KAMLOOPS FOREST REGION

Final Report
Volume I

Prepared For

B.C. Ministry of Forests
Kamloops Forest Region

Terratech Western Profile Consultants Ltd.
Salmon Arm, B.C.

March 1994
File: 211-0

R.T. Pack, Ph. D., P. Eng.
Geotechnical Engineer

terratech
WESTERN PROFILE

TABLE OF CONTENTS

APPENDICES

A. Phase I Report
B. Raw Data Cards (in Volume II under separate cover)
C. Data Summary Sheets
D. Histograms and Probability Curves Comparing Landslide and Non-Landslide Sites
E. Detailed CHAID Analysis Results (in Volume III under separate cover)

211-0J.DOC

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

This study presents the results of a 2½ year long inventory of forest landslide occurrences within the Kamloops Forest Region. Landslides greater than 100 m^3 in size or that have moved greater than 50 m have been targeted. Phase I of this study identified 970 landslides in the Region and Phase II obtained detailed characteristics of 275 of these landslides and any forest roads associated with them.

The purpose of the study has been to (1) develop or improve criteria for the prediction of landslide hazards and (2) provide assistance in improving management guidelines and assessment methodologies for sensitive terrain so as to reduce environmental impacts, maintenance requirements and rehabilitation requirements for forest roads.

The interpretations contained in this report are general in nature and largely utilize objective statistical procedures in developing landslide hazard prediction methodology and in the assessment of common road construction practices. The data base compiled by months of field work includes a wealth of data dealing with individual areas and sites and the peculiarities of each. Abundant opportunity exists for follow-up studies designed to answer more specific questions.

The ways and means of applying this data to forest practices and policy must be developed carefully by qualified individuals because many of these statistics could be easily misapplied. The limitations of the data, along with the statistical methods employed must be fully understood by those applying the data.

Several unique and somewhat different mechanisms were identified as being responsible for landslides. They include:

(1) undercutting of the natural slope by a road cut,
(2) overloading of the slope by a road fill coupled with saturation by water from a blocked culvert in a gully or creek,
(3) overloading of the slope by a road fill coupled with saturation by road surface water or diverted ditch water,
(4) the initiation of a landslide on a natural slope caused by the diversion of water off a road upslope, and
(5) purely natural processes unrelated to man's activities.

The following terrain factors have been identified as having a significant influence on the relative landslide hazard: *natural terrain slope, seepage, genetic material (geologic method of deposition), soil texture, surface slope expression (landform), soil depth, slope processes, slope position,* and *slope shape*. The following road related variables were also found to be significant in order of importance: *critical slope angle, road fill height, road cut height, drainage installation, fill slope, wood in fill, ditch depth,* and *drainage maintenance.*

The purpose of a landslide hazard prediction model is to better assess in advance the likely response of a hillside to forest road construction. The best landslide hazard prediction model developed in this study is specific to cutslope failures and uses both terrain and road-related variables. Using this model, 15% of the sites were classified incorrectly, i.e. a site with a cut-slope failure was classified as having a "Moderate" to "Low" hazard, or a stable site was classified as "High" or "Very High". By excluding road variables, the percentage misclassified by this model went up to 24%. The best hazard prediction model for all types of landslides grouped together has a misclassification percentage of 25%, and is ranked third when compared to all of the other hazard prediction models devised.

This study has found that, through geometric dependencies and given the landslide statistics, the construction of fills on slopes greater than 33° often leads to a geometry that is potentially unstable. This is in approximate agreement with many standard practice guidelines presently in use that require consideration of full bench cuts on slopes in excess of 33° (65%).

The vast majority of failed road segments examined have inside ditches at or less than a depth of 0.5 m. Most of the adjacent road segments had similarly shallow ditches. Though weakly supported by the data, it is likely that maintaining a standard road ditch depth of at least 0.5m may improve the road drainage and help prevent water from running uncontrolled over fill slopes. This would likely result in a significant reduction in landslide occurrences within the region.

The results of this study indicate a large percentage of roads with poor provisions for drainage that would not meet existing standards. This would strongly indicate that the future application of existing standard procedures for the control and maintenance of drainage on roads would contribute significantly to the reduction of landslide occurrences in the Kamloops Forest Region.

It has been found that a high incidence of landslides is associated with fills dominated by woody debris. Though logs, stumps, etc. initially reinforce the fill, it appears that the higher incidence of landslides in wood-dominated fill is due to some of the wood rotting away and causing a destabilization of the fill.

Trial modifications to the Mass-wasting Hazard Assessment Key used in PHSP assessments involves changes to factor weights, along with the removal of the *R-Factor* and *Depth to Water Restricting* variables. These changes have resulted in slightly better classification results. However, the improvement is considered minor. In view of the fact that the inventory data does not properly test the regional utility of the R-Factor, it hard to justify any major modifications to this now well-established assessment tool on the basis of the landslide inventory data.

A useful five-class stability hazard mapping methodology has been developed based on landslide inventory data. The methodology first involves assigning a "preliminary hazard class" determined strictly by the natural slope angle. Then, depending on the specific terrain conditions, this class is either upgraded or downgraded to the next higher or next lower class. This method should work well in practice as a map can first be segmented according to slope classes largely derived from contour mapping or aerial photo interpretation. These preliminary classes can then be modified according to the results of field checking.

It should be remembered that a hazard classification based solely on terrain variables will fail to anticipate the actual hazards that would exist following road construction. The final predictive accuracy and utility of a stability hazard map will vary greatly, depending on the complexity of the terrain in the study area. It is therefore important that this be acknowledged and disclosed to the user in an understandable manner.

Because the Forest Practices Code is quite general in nature, many of the specifics of design and construction are left to the forest professional or forest worker to determine. Several minor modifications have been recommended for Chapter 9 of the Code.

A. INTRODUCTION

A.1 Background

This report presents the results of Phase II of an inventory of "Forest Landslide Occurrences" within the Kamloops Forest Region. Phase I involved an aerial reconnaissance study with it's primary aim being to identify watershed with clusters or groups of landslide occurrences. The purpose of Phase II has been to follow-up with ground data collection at selected landslide sites, then provide an analysis of the implication of this data to road engineering and landslide hazard prediction.

Phase I of this study was completed in the fall of 1991 and inventoried a total of 970 landslides. Phase II data collection was completed during the summer and fall of 1992 and 1993, and assessed in detail a total of 275 landslide sites.

The terms of reference of Phase I were to: (1) inventory all recent (1987 to present) slumps and/or slides within the Region, (2) map the locations and general size of occurrences (ideally greater than 100 m^3 in volume and/or greater than 50 m in down-slope movement), (3) where possible, record the likely cause of the occurrences, and (4) indicate the need for further study.

The work in Phase I was completed by (1) interviewing key personnel within the Ministry of Forests and Forest Companies who had personal knowledge of the location of landslides that have occurred since 1987, (2) conducting fixed-wing reconnaissance flights over each of the seven Forest Districts over a 7-day period, and (3) compiling the data into tables and presenting the results. The report giving the results of Phase I is provided in Appendix A.

A.2 Objectives

The objectives of Phase II as originally proposed were:

- Assess the terrain and road construction variables that were associated with or caused past landslide occurrences.

- For comparison purposes, collect data in the surrounding areas which did not experience problems.

- Use data from adjacent areas to develop or improve criteria for the prediction of landslide susceptibility utilizing this data.

- Provide assistance in improving management guidelines and assessment methodologies for sensitive terrain in order to reduce environmental impacts, maintenance requirements and rehabilitation requirements.

The data collection portion of Phase II was completed during the summer and fall of 1992 and 1993. In 1992, the eastern portion of the Kamloops Forest Region was targeted including Clearwater, Salmon Arm, Vernon, Kamloops, and Penticton Forest Districts. In 1993, the western portion was covered including Lillooet, and Merritt Forest Districts.

Specific guidelines and methodologies which have been reviewed in this study include (1) "Hazard Assessment Keys for Evaluating Site Sensitivity to Soil-degrading Processes - Interior Sites, Field Guide Insert 8", (2) "Landslide Hazard Mapping Guidelines for British Columbia" along with "Regional Stability Mapping Guidelines", (3) Road Construction, and Maintenance Guidelines in the "Forest Practices Code", and (4) critical road construction practices in general.

B. METHODOLOGY

B.1 Data Collection

The data collection program for Phase II has emphasized the observation of site-specific terrain and road characteristics at, and immediately adjacent to, landslide sites. Of importance in this study has been the comparison of sections of forest roads that have experienced stability problems with areas that have not had problems. The data collection methodology therefore includes a sampling of both landslide and non-landslide areas.

In order to be representative of the Region, a large number of areas required inspection. The budget did not allow a detailed ground-truthed terrain analysis of each watershed. It was also felt that mapping based on aerial photo interpretation alone would not be meaningful in assessing the specific terrain at landslide sites. It was therefore proposed that road exposures within the watershed be used as the means of terrain sampling. The advantages of this approach have been:

- The forest roads were able to provide a good view of the soil characteristics and depth (as in a continuous soil test pit).
- A natural sampling bias toward accessible or developable terrain resulted. This was desirable as it is representative of the type of terrain most likely to be developed in the future. Extremely rough or steep areas such as rock cliffs are not likely to be developed and should rightfully not be included in the sample.
- While terrain data was being collected, road data was also sampled thus providing valuable insight into the terrain response to ground disturbance in a variety of situations.
- Landslide and non-landslide data can be collected in groups of road segments that have all been subjected to similar climatic conditions, i.e. rainfall and snowmelt.
- The use of "polygon" based measures of landslide frequency are avoided. Therefore, problems associated with cartographic representations (lumping vs. splitting polygons), mapper bias, etc., do not need to be dealt with. This is considered appropriate as landslides typically respond to site-specific factors which are usually not accurately represented by polygons in complex terrain.

The disadvantages to this approach were:

- The roaded areas were not necessarily representative of the entire watershed and therefore precluded an unbiased analysis of natural landslide occurrence densities for different terrain types. As this was not a primary focus of the study, this disadvantage was considered acceptable.
- The extent of the road network was limited in certain areas.

- causes of landslides are based on judgments, sometimes several years after occurrence. In some cases, there was no way of definitely knowing the cause of a given slide.

- there are some difficulties in lumping and/or splitting ranges of parameters within a road section. However, these difficulties are somewhat less severe that those associated with polygon mapping.

The road network within the vicinity of the landslide cluster was sampled using standardized data collection sheets that included (1) natural terrain data, and (2) road prism data. Each road segment that contains a fairly homogeneous set of terrain and road data served as an individual sample and had a specific road length recorded in the data set[1].

Where road-related landslides are encountered within the segment, in addition to (1) and (2) above, landslide-specific data was also collected. The smallest landslide assessed as dictated by the Ministry was 100 m^3 in size or should have moved at least 50m. An example of the data collection sheet used in the study showing the terrain, road and landslide data subsets is provided as Figure B-1.

All bladed structures including skid roads or back-spar trails were considered as candidates for data collection. Where landslides in undisturbed areas were assessed, only the landslide-specific data and terrain data were collected.

For clarity, the following terminology has been adopted for this study and is shown diagrammatically in Figure B-2:

- **Area** - An area within the Forest District that can be uniquely identified. Usually a creek or watershed.
- **Road** - The name of the road or spur on which the data was collected.
- **Site** - A unique location on the road or within the area where a landslide had occurred.
- **Road Segment** - a section of road whose unique characteristics have been identified. Each road segment had a unique data card associated with it.
- **Group** - a group of road segments at and immediately adjacent to a landslide site.

Data was collected at a total of 275 sites representing 701 road segments across the region. A breakdown of the number of landslides sites visited in each Forest District is provided in the following table:

[1] A road segment which is defined by a combination of (1) a specific construction method and (2) a natural terrain unit, is often referred to as a "design sector" in geologic engineering vernacular.

LANDSLIDE INVENTORY - FIELD DATA FORM

Area:________Road________Segment___________Sheet of
Description:______________________________Date: / /
Segment - km_____ to km ______. D M Y

TERRAIN DATA

Upslope (°)	MIN	MAX	**Downslope (°)**	MIN	MAX
Soil Class			**Biogeoclimatic Subz/Var =**		
Gradation	Poorly Moderately Well N/A				
Density	Loose Compact Dense N/A				
Genetic Material	M C F^G F L^G L R (Type): Other:				
Surface Express	b c f h m r t v Soil Depth: <50 cm , 51-100 cm , >100 cm				
Processes	A F R V None Other:				
Slope Position	Top Upper Mid Lower Toe				
Slope Shape UD	Concave Convex Straight				
Seepage	Continuous Intermittent None				

ROAD DATA

	Minimum	Maximum		Minimum	Maximum
Road Width (m)			**Ditch Depth (m)**		
Fill Height (m)			**Cut Height (m)**		
Fill Slope (°)			**Cut Slope (°)**		
Gradient (%)					

Drain Culverts :		**Ck Culverts :**		
Drain Install.	None	Poor	Fair	Good
Drain Maint.	None	Poor	Fair	Good
Wood in Fill	Little	Some	Dominant	Other:
Const. Method	Backhoe	Dozer	Blasting	Other:
Road Prism	Full Bench	Part Bench	Gully Fill	Cut-Fill
M.M. Potential	Low	Moderate	High	

LANDSLIDE DATA - Sta.

Dimensions (m)	LENGTH =	WIDTH =	DEPTH =	TRAVEL =		
Type	D-AVALANCHE	D-FLOW	SLUMP	EARTHFLOW		**DATE** OCCURRED
Headscarp Location	UNIFORM CUTSLOPE	HEADWALL FILLSLOPE	SIDEWALL SWALE	BENCHFACE		
Water Type	GROUNDWATER	SURFACE	SHEET			**SOURCE**
Water Source	SPRING	CHANNEL/RILL	CULVERT	DITCH	ROAD SURF	
Soil Strength Contribution	UNDERCUTTING	OVERLOADING	FILL ROT	ROOT LOSS	N/A	**X-REF**
Destination	GULLY	CREEK	FAN	LAKE		H_2O QUALITY

NOTES/SKETCH

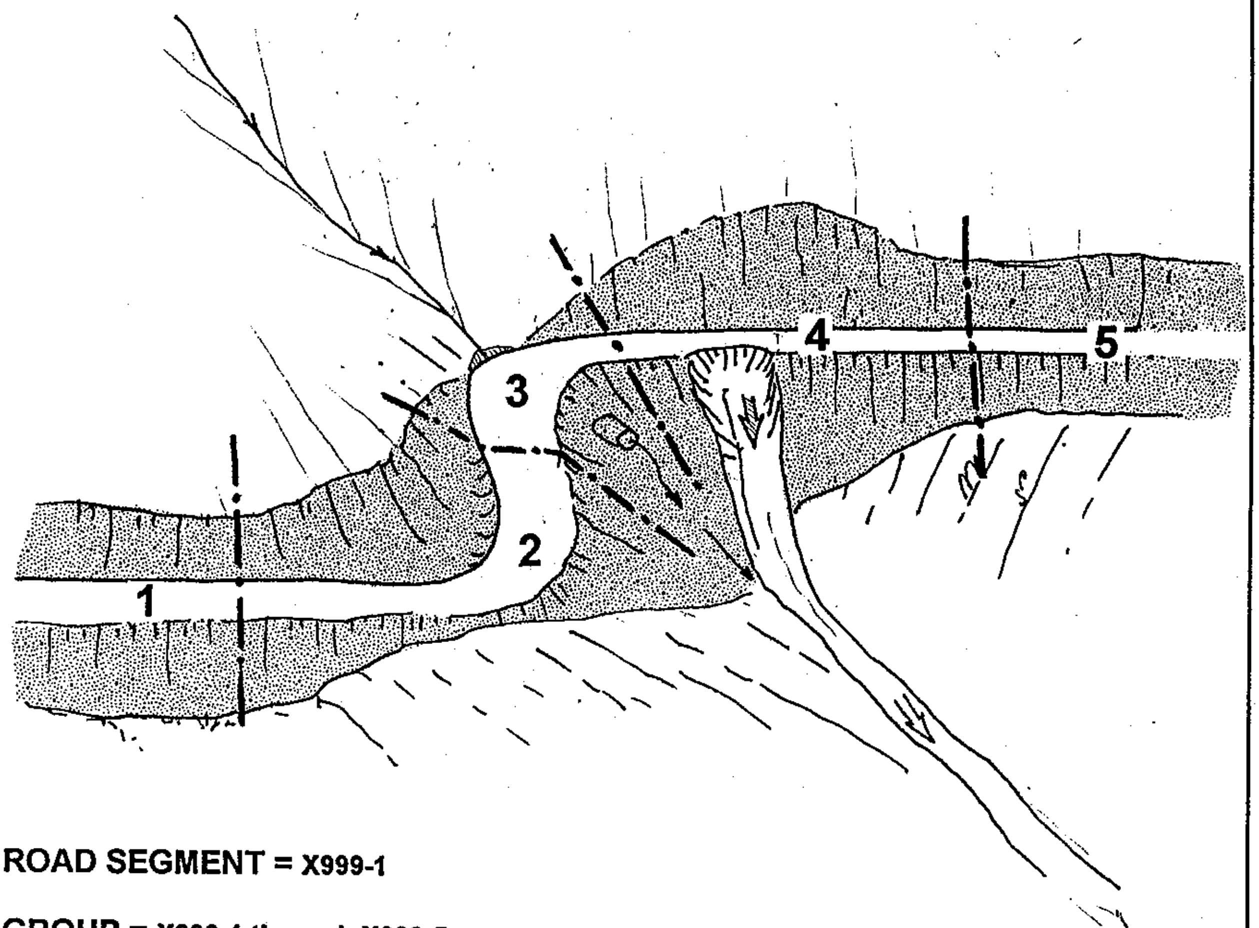
Figure B-1. Landslide Inventory - Field Data Form

terratech
WESTERN PROFILE

AREA - NO-NAME CREEK

ROAD - "EASYGOING" ROAD

SITE - X999



ROAD SEGMENT = X999-1

GROUP = X999-1 through X999-5

LANDSLIDE SITE = X999-4

NON-LANDSLIDE SITES = X999-1
X999-2
X999-3
X999-5

Client	MINISTRY OF FORESTS
Title	DEFINITIONS FOR DATA COLLECTION
Job No. 211-0	Date 9 Mar '94
FIGURE B-2	

terratech
WESTERN PROFILE

FOREST DISTRICT	#
Clearwater	17
Kamloops	5
Lillooet	35
Merritt	45
Penticton	22
Salmon Arm	60
Vernon	91

B.2 Data Analysis Methods

The data collected using the methodology described above was used in various ways. All data was collected on the same field sheet which has three sections including: (1) landslide data, (2) road data and (3) natural terrain data. Detailed descriptions of the variables included in the field sheets are given in Section C. Depending on the site, one, two or three of these sections were filled out. Table illustrates how this data was used in combination to develop a hazard or susceptibility prediction model.

Table B-1 - Types of data required for different types of hazard prediction.

Landslide Data	Disturbance Data	Terrain Data	Correlated with	Disturbance Data	Terrain Data	Hazard Prediction
X	X	X	----->	X	X	on existing roads
X	X	X	----->		X	on future roads
X		X	----->		X	future natural landslides

In addition to providing insight into the natural terrain factors that contribute to landslide susceptibility, the collected data also highlights road prism geometries, drainage characteristics, etc. that are the most associated with road-related landslide occurrences. Having identified these characteristics for various types of terrain, it is then possible to review the existing construction guidelines and propose changes which will have the greatest chance of reducing risk of both on-site and off-site impacts.

Various statistical analyses have been used to identify the terrain and disturbance characteristics that are most associated with landslides and therefore can do the best job of anticipating hazards. A brief summary of the methods used follow. For a more detailed explanation, the reader is referred to several excellent text books on the subject.

Individual Variables. First, single variables have been analyzed individually in what it termed a "univariate analysis". In this case the summary statistics (i.e. mean and standard deviation) for variables such as *average slope* are compiled for road segments associated with landslides and compared to the summary statistics for those sites where landslides did not occur. In the case where the variable is categorical such as *genetic material*, the frequency counts in each category are compared between landslide and non-landslide sites. By making such comparisons it is possible to determine which variables change most "significantly" between the two types of sites, "landslide sites" and "non-landslide" sites. The objective is to find the variables which have significantly different statistics for the two populations.

A well-known and widely used statistical test of the difference between the means of two populations is the **T-Test**. This test is applicable to "continuous" variables such as *average slope* and determines the probability that the mean values for landslide and non-landslide sites are from the same population. The lower the probability value (P), the more likely that the variable is directly related to the likelihood of a landslide occurring. Typically, if the P is less than 0.01, then the variable is considered to be a "significant" predictor. A similar test can be applied to "categorical" variables and is called the **Chi-Squared Test** (χ^2). This test determines the same probability value P by using a cross-tabulation technique. These two tests have been used in this study in order to help identify those terrain and road variables that appear to influence landslide occurrences.

Variable Combinations. It is possible to analyze several variables at once to determine how well different combinations can predict landslide occurrences. This type of analysis requires more complicated "multivariate techniques". Because the data collected in this study is a combination of both categorical and quantitative variables, the use of traditional discriminant analysis methods are not appropriate[2]. Statisticians have developed better techniques for categorical variables such as logistic regression, logit analysis and the more recently developed **CHAID** analysis. A CHAID analysis has been used in this study due to the writer's familiarity with its theory, its easily applied results, and excellent capabilities demonstrated by a recent study dealing with landscape variables in B.C.[3]

CHAID which stands for Chi-Square Automatic Interaction Detection uses a classification tree where each split in the tree optimizes the separation of landslide sites from non-landslide sites based on the best categorical predictor variables. Those branches of the classification tree which include the highest percentage of landslide sites vs. non-landslide sites would be considered the most susceptible. Once a primary split is made, secondary splits based on a newly discovered second-best predictor variable can be made. This computer method[4] has an ability to single out the most important predictor variables and

---

[2] Traditional linear discriminant analysis assumes that all variables are continuous and normally distributed. The data collected in this analysis do not meet both of these assumptions.

[3] Badesso, E. and Pack, R.T. 1992. Viewer perception of visually effective green-up. Proprietary report to Ministry of Forests, Victoria, B.C.

[4] Terratech uses CHAID software developed and distributed by SPSS Inc., one of the most widely used software companies in North America.

disregard the rest. Hence, meaningful terrain classes, i.e. unique groups of terrain characteristics, can be derived from a myriad of categorical data in an objective way.

Past statistical landslide studies similar in nature to this study have derived multi-factor risk classifications that would fit well in a classification tree structure produced by CHAID[5]. CHAID also avoids the need to arbitrarily define terrain classes in advance of the statistical analysis as has been done in the past[6].

---

[5] See the 15 class and 4 variable structure presented in Table 7 of Rollerson, T.P. 1992. Relationships between landscape attributes and landslide frequencies after logging: Skidegate Plateau, Queen Charlotte Islands. This structure is equivalent to a tree with four levels of branching given the four variables.

[6] See page 2 of article by Rollerson, T.P., Howes, D.E., and Sondheim, M.W. 1986. An approach to predicting post-logging slope stability for coastal British Columbia., In: Proceedings of NCASI West Coast Regional Meeting, Portland, Oregon, USA, 14 p.

C. DESCRIPTION OF DATA

In this section, the definitions of the individual types of data (variables) are discussed. The definition, description, and frequency tabulation of the entire data set is given in order to get a feel for each variable. Table C-1 attached at the end of Section C, gives a summary of the field data variable definitions. A complete set of data summary sheets and frequency tabulations (histograms) are found in Appendices C and D respectively.

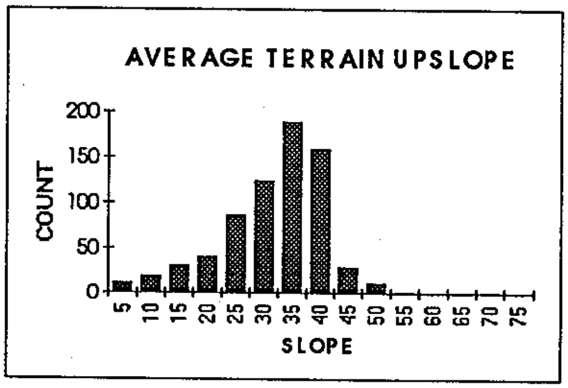
C.1 Header Data

The definitions of the terms *Area, Road, Segment, Site,* and *Group* are illustrated in Figure B-2. In addition to this information, the location of the beginning and end of the road segment is recorded. The location is expressed in kilometers and is relative to an arbitrarily chosen point on the road (sometimes the landslide site). It is a convenient way to record segment lengths and location relative to one another.

C.2 Terrain Data

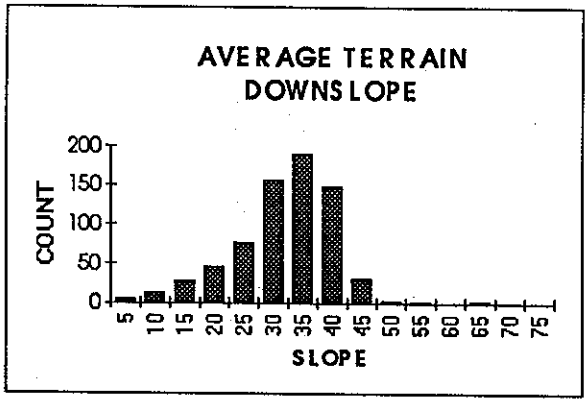
C.2.a. Upslope

The *Upslope* variable is a measure of the natural terrain slope above the road location expressed in degrees. Both a minimum and maximum value within the road segment was recorded. In areas where there was a wide range of slopes within a segment, recording the maximum and minimum helps determine the width of the range. A frequency tabulation for the average of the maximum and minimum for the landslide inventory data set (701 total sites) is shown below.



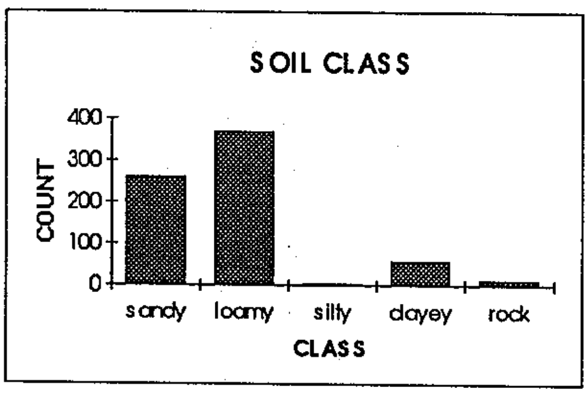
C.2.b. Downslope

The *Downslope* variable is a measure of the natural terrain slope below the road location expressed in degrees. Both a minimum and maximum value within the road segment was recorded. In areas where there was a wide range of slopes within a segment, recording the maximum and minimum helps determine the width of the range. The following graph illustrates the frequency tabulation for the average of the maximum and minimum for the landslide inventory data set (701 total sites).



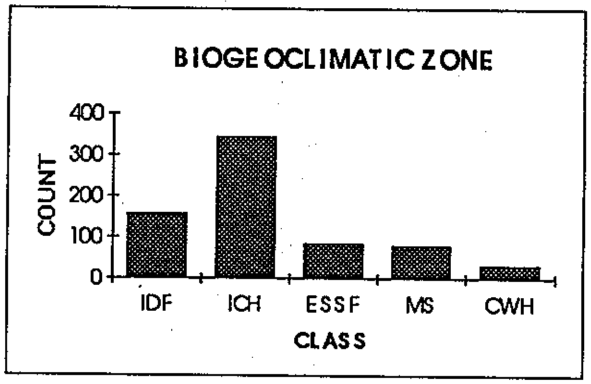
C.2.c. Terrain Soil Class

The *terrain soil class* has been estimated at each site using the soil texture triangle of the "Canadian System of Soil Classification, Fig. 37". It is based on the estimated percent sand, silt and clay. Following is a frequency tabulation for the soil classes lumped into the sandy (LS, S), loamy (SL, L, SiL), silty (Si), and clayey (SiCL, CL, SCL SC, C, HC).



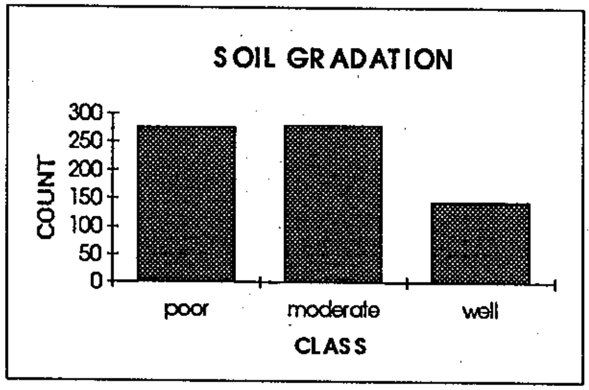
C.2.d. Biogeoclimatic Subzone and Variant

The *Biogeoclimatic Subzone and Variant* has been determined at each site using existing maps of the area. The subzones were not determined by direct observation. Following is a frequency tabulation for all sites in the database.



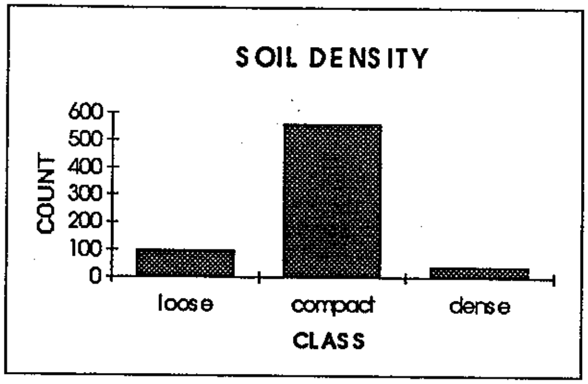
C.2.e. Soil Gradation

Soil gradation is determined by estimating the degree of sorting. The method used is the same recommended by the Unified Soil Classification System for distinguishing between poorly-graded and well-graded soils (e.g. SW verses SP). Following is a frequency tabulation for this variable using the entire data set.



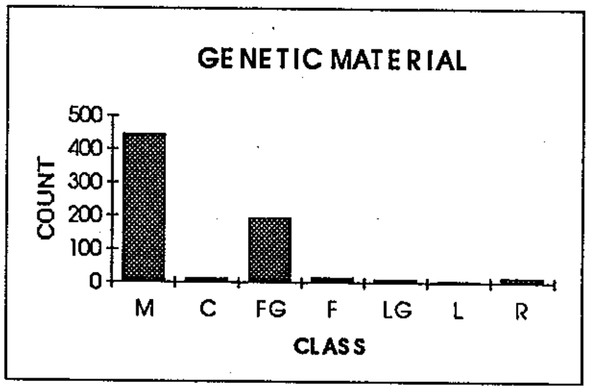
C.2.f. Soil Density

Soil density is subjectively determined by probing the soil with a shovel head or hand pick. The criteria for indicating compact versus dense soil is probably the most problematic. Ablation tills would normally fall within the compact definition while basal tills which include a fairly fine matrix are considered dense. As can be seen from the following frequency tabulation, most of the soils inventoried are compact.



C.2.g. Genetic Material

Genetic Material is defined in detail by the "Terrain Classification System, 1988". The frequency tabulation for this variable is shown below, where M = morainal (glacial), C = colluvial, FG = fluvioglacial, F = fluvial, LG = glaciolacustrine (glacial lake), L = lacustrine (lake), and R = rock.

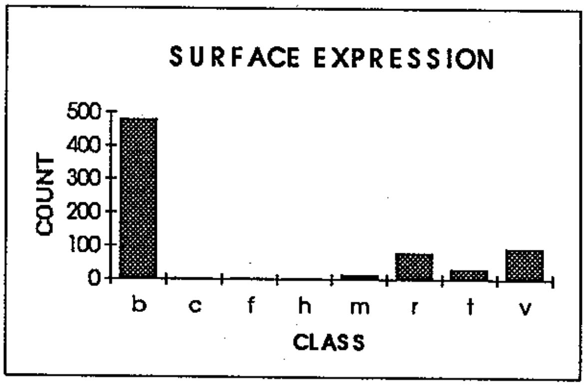


C.2.h. Rock Type (if present)

If bedrock is observed, the lithology of the rock was recorded. Most of the terms indicated are fairly general. In cases where the exact lithology (e.g. biotite schist) is not certain, a more general description is used (e.g. banded metamorphic).

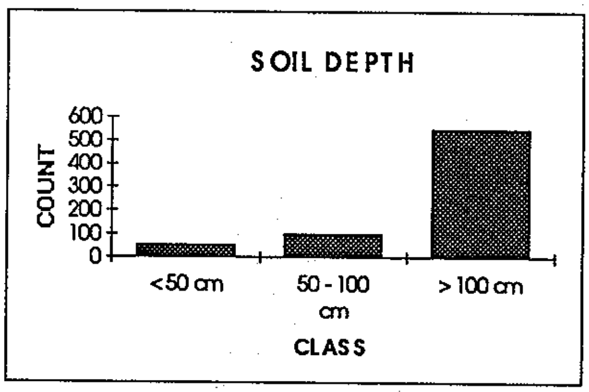
C.2.i. Surface Expression

The surface expression is defined in detail by the "Terrain Classification System, 1988". Following is a frequency tabulation for this variable where b = blanket, c = cone, f = fan, h = hummocky, m = rolling, r = ridged, t = terrace & v = veneer.



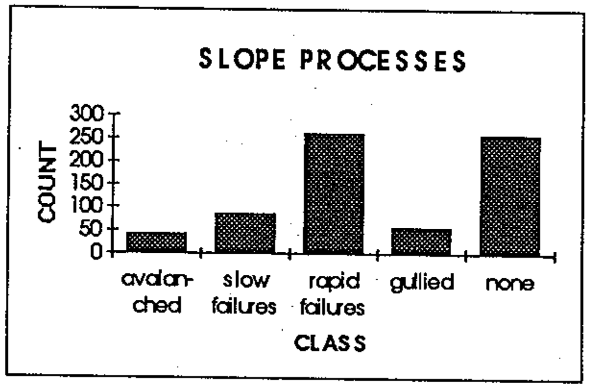
C.2.j. Soil Depth

Soil depth has been determined largely by examining the road cut slope. The average depth over the road segment has been estimated and assigned to one of three classes: shallow (<50cm), moderate (50-100cm), and deep (>100cm). The frequency tabulation for this variable is:



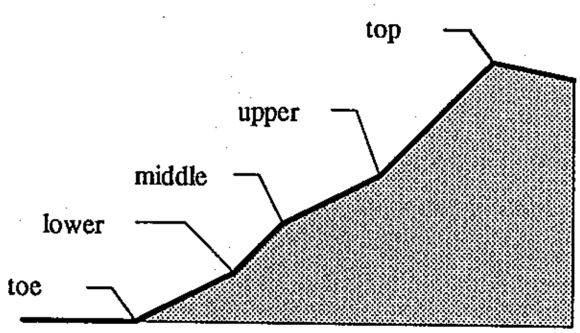
C.2.k. Surface Processes

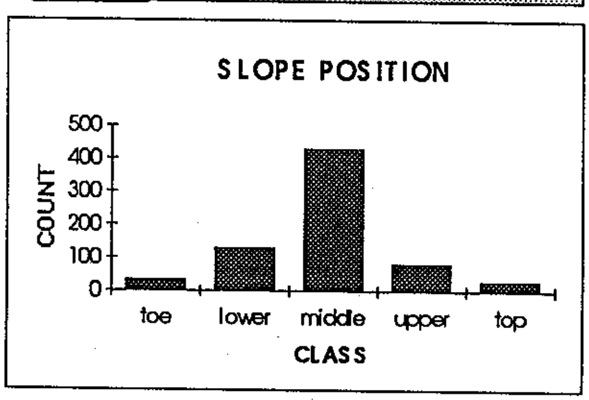
The surface processes are defined in detail by the "Terrain Classification System, 1988". The original intent of this study was to indicate a whether or not indicators of a natural landslide process was present at the site. Unfortunately, the data collection was not consistent in this regard since, on occasion, the man-caused landslides were indicated on the data collection form as a "rapid failure" or "slow failure". Thus the utility of this variable in determining the importance of evidence of landsliding in advance of road construction has been compromised. Careful sorting through the data card and photographs may be able to resolve some of these problems but was not attempted under the constraints of the current budget. A frequency tabulation for this variable follows:



C.2.l. Slope Position

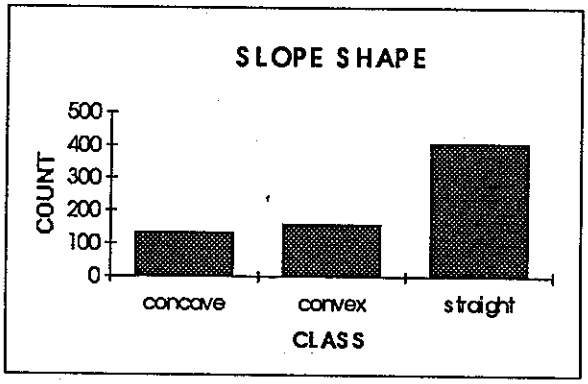
Slope position is a measure of the relative position of the road segment on the mountain side. The following diagram shows the relative position of each category. Below this diagram is a frequency tabulation or each slope position for all sites inventoried.





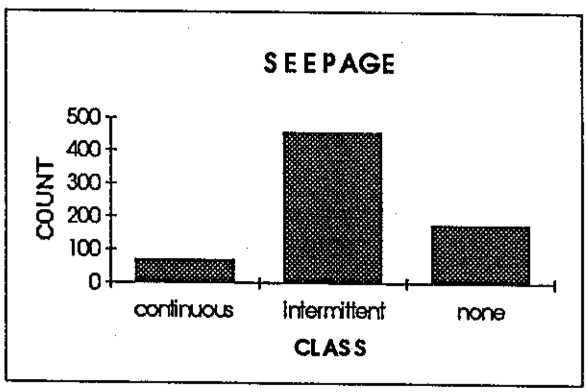
C.2.m. Slope Shape

This variable is a measure of the shape of the slope in the **fall line,** i.e. up and down the slope. A slope where it is steeper below but is rounding out to be more gentle above would be considered convex. On the other hand, where it is steeper above and more gentle below, the slope is concave. Otherwise the slope is straight. The frequency tabulation for this variable using the entire database follows.



C.2.n. Seepage

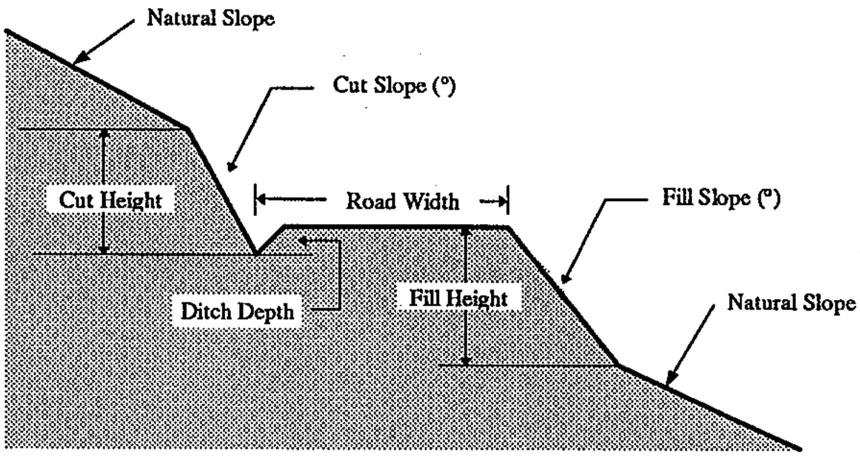
Evidence of ongoing or intermittent *seepage* was noted at each site visited. If water was observed emerging from the road cut and wetland vegetation was present, the site was considered to be experiencing continuous seepage. If on the other hand evidence was found that water had at one time been emerging from the face as indicated by rills, etc., but is now dry , the site was labeled as having intermittent seepage. It is acknowledged that many sites that experience intermittent seepage would leave little evidence and would therefore be classified as "dry". The bias in the data therefore would be toward underestimation of water. It should be noted that the detection of seepage on undisturbed natural slope would be more difficult than when observed on a road cut. Following is a frequency tabulation for this variable for the entire database.



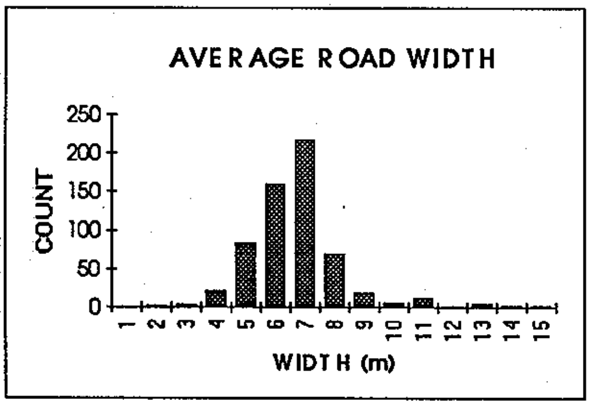
C.3 Road Data

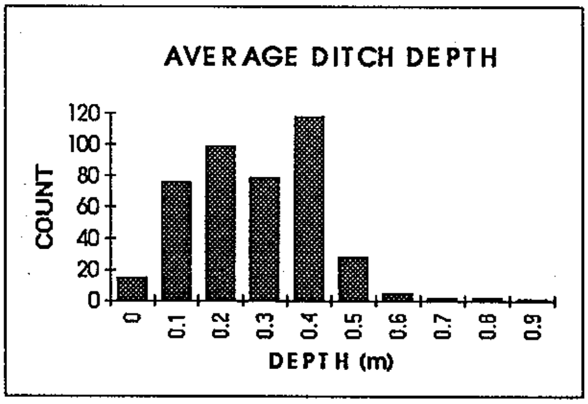
C.3.a. Road Dimensions

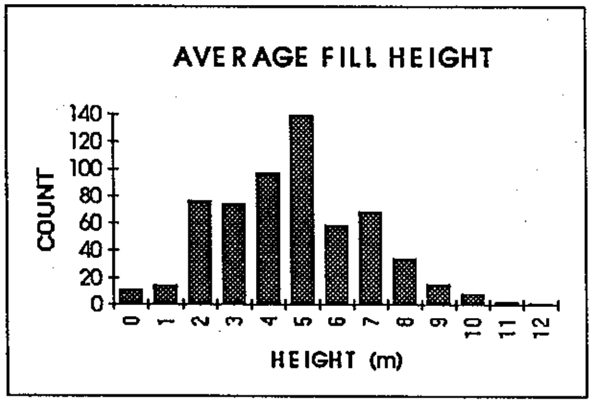
Road width, ditch depth, fill height, cut height, fill slope, and *cut slope* were for each road segment. Both the maximum and minimum dimensions were recorded and the average calculated. The definitions for these dimensions are shown diagramatically below.

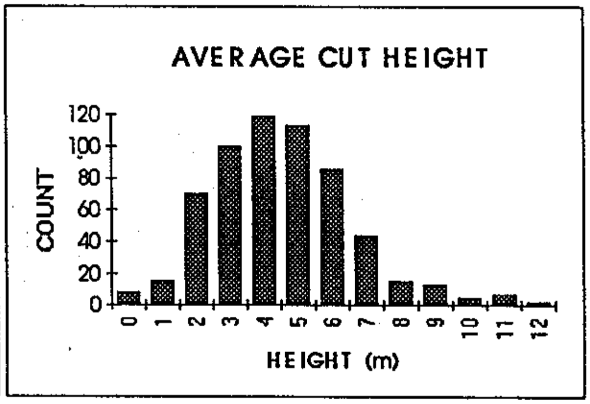


Following are frequency tabulations for the average values of these dimension for the entire inventory data set.

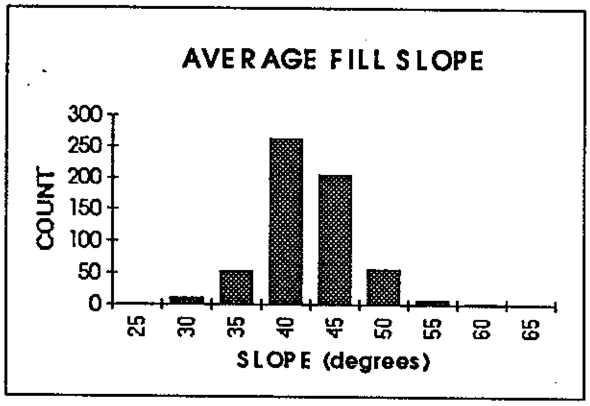


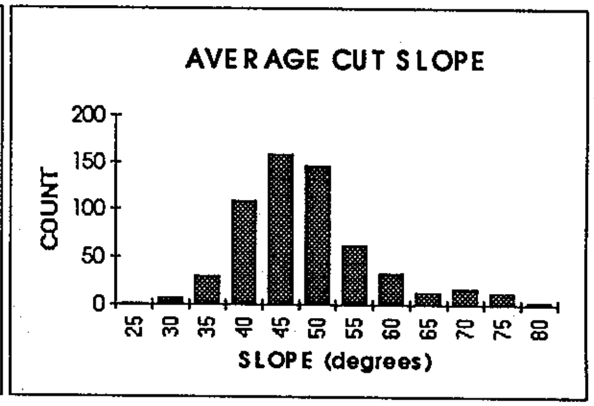






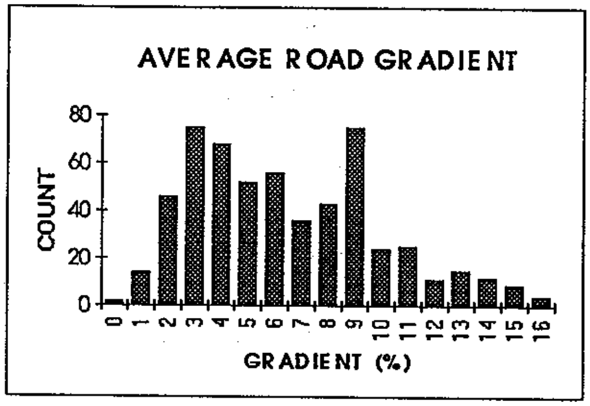
terratech WESTERN PROFILE





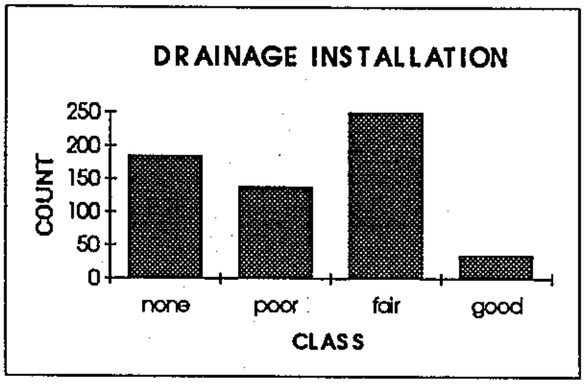
C.3.b. Road Gradient

Minimum and maximum *road gradient* is measured along the road segment in percent. A tabulation of the average of the minimum and maximum for the entire database si shown below.



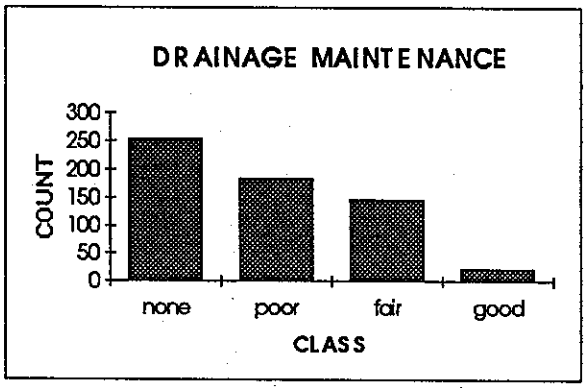
C.3.c. Drainage Installation

This variable is a qualitative measure of how well drainage works have been installed within the road segment. The adequacy of ditch and culvert locations (not maintenance) is of primary interest. If ditches and culverts are non-existent, the "none" was circled on the data collection form. If some attempt was made to provide measures for drainage, but it was poorly done, then "poor" was circled. Otherwise, either "fair" or "good" was indicated. Following is a frequency histogram for the entire data set. If the road segment is classified as "good", the standard textbook methods of drainage installation would have been used.



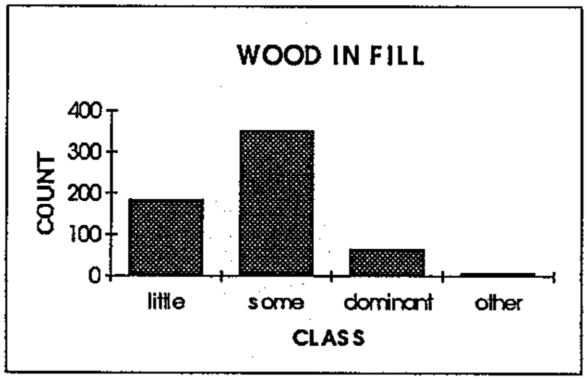
C.3.d. Drainage Maintenance

This variable is a measure of how well the drainage works, if installed, were maintained. Items assessed include non-functioning culverts, poorly maintained or blocked ditches, road surface erosion, etc. The classes "none", "poor", "fair", and "good" are used as qualitative measures. Following is a frequency histogram from the entire data set for this variable.



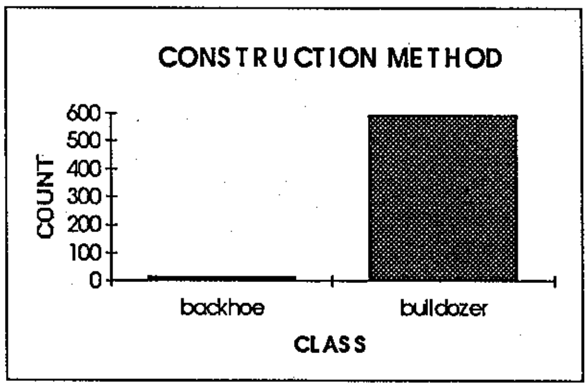
C.3.e. Wood in Fill

This variable indicates the amount of logs, stumps, and wood debris that has been incorporated into the fill materials. If the "dominant" category has been indicated, this means that the fill is obviously partly supported by the reinforcing effect of the wood. This is an indication of the vulnerability of the fill once the wood rots and the reinforcing support is lost. If wood is noted in the fill, but is not largely supporting it, the "some" category is indicated. Otherwise "little" is usually indicated. Following is a frequency histogram for the *wood in fill* variable compiled for the entire data set.



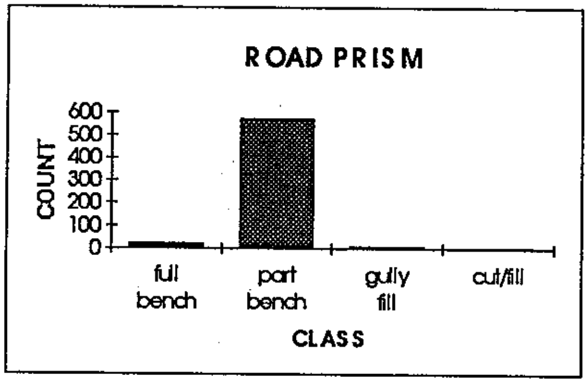
C.3.f. Construction Method

The *construction method* has been estimated using subjective judgment. This variable was somewhat difficult to judge in many cases since the distinction between dozer construction and poor back-hoe construction is indistinct. As it turns out, most of the road assessed were of the dozer-type quality as indicated in the following frequency histogram.



C.3.g. Road Prism

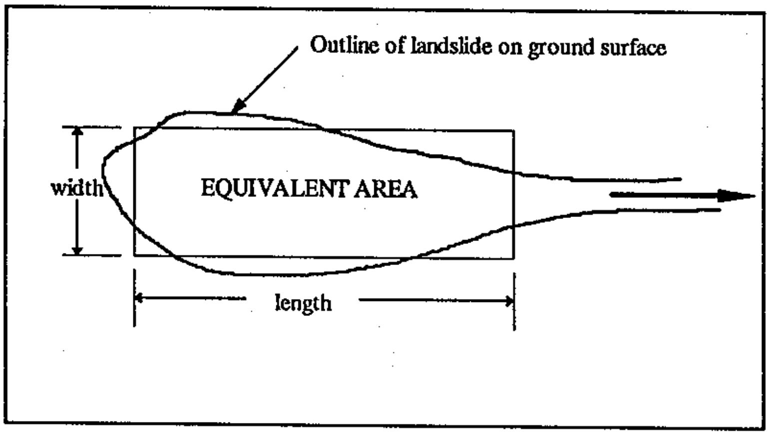
This variable is a measure of the placement of the road prism on the hill side. "Full bench" indicates that the road is purely in cut with no fill placed on the slope. "Part bench" is the most typical situation where the cut and fill volumes are balanced. "Gully fill" indicates a location where a gully is being crossed and a road fill extends off both shoulders of the road. The "cut/fill" category indicates a road segment where there is a close succession of gullies where the road alternates between full cut and full fill. This situation was found to be relatively rare as individual road segments were normally broken out to include either cut or fill. Following is a frequency histogram for this variable for the entire data set.



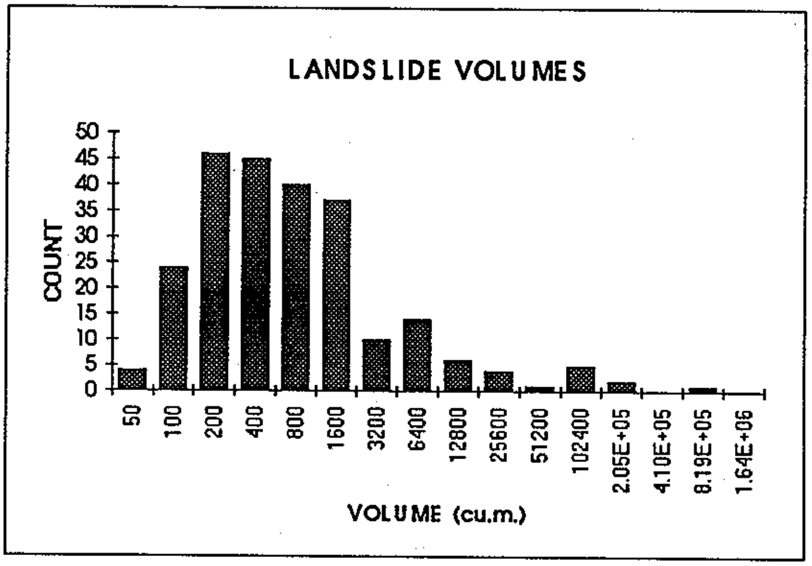
C.4 Landslide Data

C.4.a. Dimensions

The average dimensions of the landslide were recorded in such a way to indicate a volume estimate by multiplying the 3 dimensions. The following sketch shows the intent of the measurements.

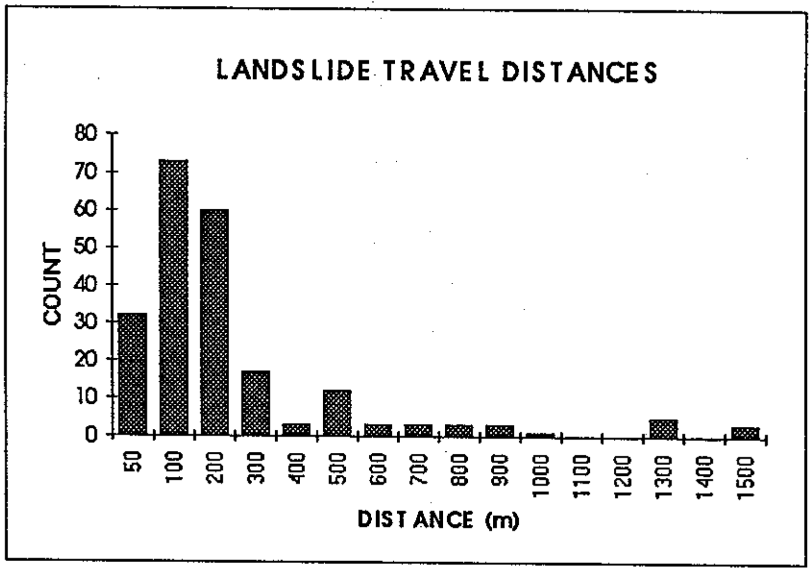


Landslide volume is calculated as a product of the length, width, and depth of the initiation zone only. Once the slide is mobilized and begins to pick up material during transportation, the volume often increases (as in a debris flow). However, this variable does not reflect this total volume. A frequency histogram of landslide volumes for the study follows.



C.4.b. Travel

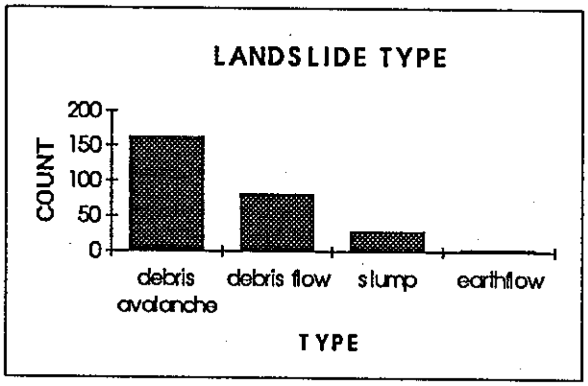
This variable is an estimate of the distance the landslide had travelled from the headscarp to the toe of debris in the deposition zone. Usually, any significant distance is associated with a debris flow. Following is a frequency histogram for this variable.



C.4.c. Landslide Type

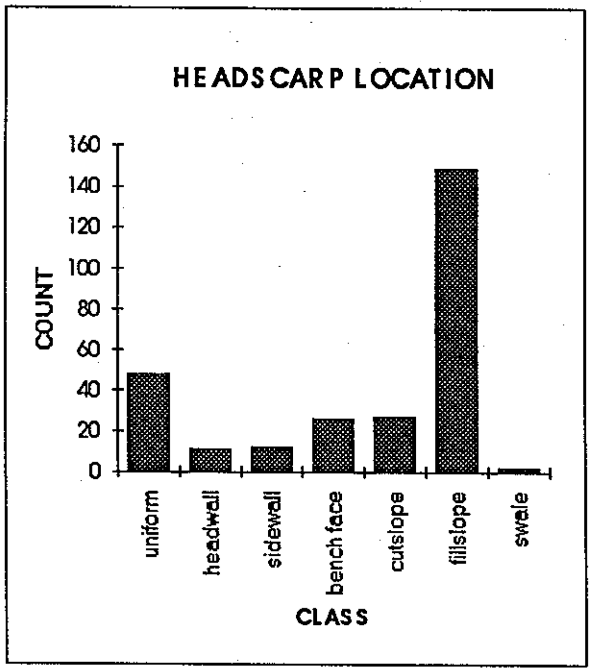
Landslide type indicates the fundamental process responsible for the movement. Four fundamental types were inventoried. A **debris avalanche** is characterized by an initial rapid translational movement that quickly transforms into a turbulent "scattering" or spreading of debris downslope. There generally is not enough soil water in debris avalanches to cause flow-like behaviour and the debris often dissipates on broad uniform slopes or benches. A

debris flow is characterized by flow-like behaviour where the initial landslide transforms into a slurry. This type of landslide is capable of traveling long distances down gullies and is responsible for the formation of debris fans at the mouth of canyons. **Slumps** usually involve deep-seated rotational-type failure, often where silty and clayey soil predominate. These are generally slow moving and sometimes retrogress upslope. **Earthflows** involve a slow "glacier-like" movement characterized by longitudinal and transverse cracking associated with slow deformation. This type of landslide can occur on gentle slopes where clayey soils with low strength slowly yield due to excess porewater pressure. The frequency histogram of the types of landslides inventoried in the Kamloops Forest Region follows.



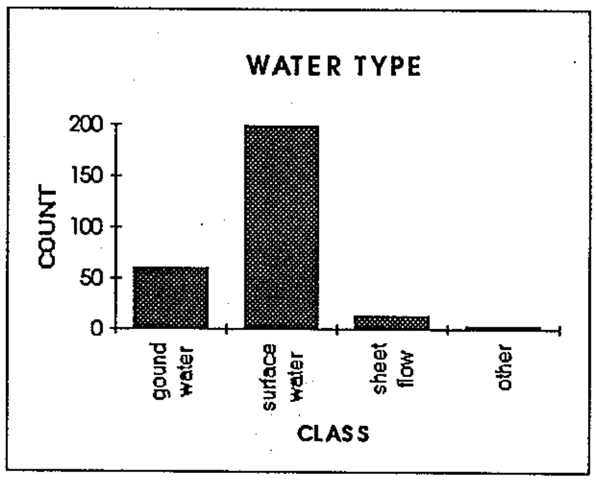
C.4.d. Headscarp Location

Headscarp location indicates where on the hillside the landslide initiated. If the landslide initiated within a road prism, this variable indicates whether or not it occurred within the **fill slope** or the **cut slope.** If the landslide initiated within an undisturbed gully, whether it occurred at the **headwall** or **sidewall** of the gully is indicated by this variable. **Swale** indicates a headscarp location in a shallow and subdued hollow or gully that is not sharply incised into the slope. **Bench face** indicates that the landslide initiated just below a break in slope of the top of a natural bench. Otherwise, a **uniform slope** is indicated. Following is a frequency histogram for this variable.



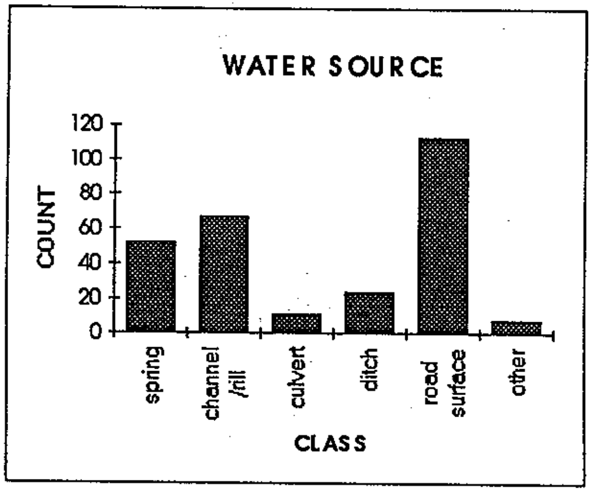
C.4.e. Water Type

This variable indicates the type of water responsible for or contributing to the landslide, whether it be **groundwater** in the form of a spring or seep or **concentrated surface water** from a ditch or gully. If unconcentrated **sheet flow** is responsible, this is also indicated. Following is the frequency histogram for this variable.



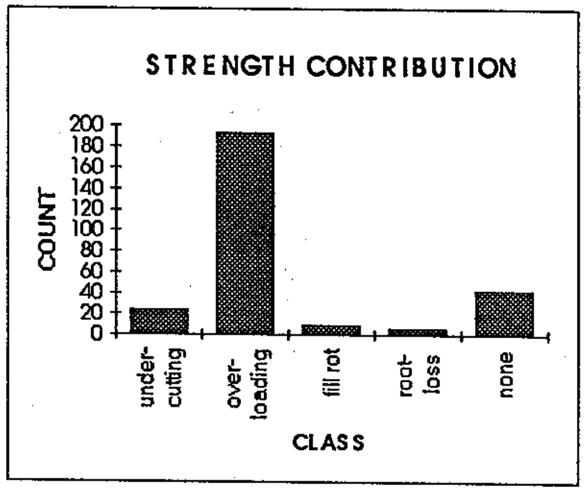
C.4.f. Water Source

This variable indicates the origin of water entering the landslide area. In other words, it is the source of the water whether it be from a **spring, channel** or **rill, culvert, ditch**, or **road surface.** Following is a frequency tabulation for all landslides inventoried.



C.4.g. Soil Strength Contribution

The variable *soil strength contribution* indicates factors that may have affected the applied soil stresses within the hillside. These factors include **undercutting** such as when a road undercuts the hillside with a cut bank, and **overloading** such as when a wedge of fill is placed on a slope. Factors which affect soil strength include **fill rot**, i.e. where buried stumps or logs within the fill may have rotted and therefore lost some reinforcing capability, and **root loss**, i.e. where the cohesive or reinforcing effect of tree roots is lost due to deforestation. Following is a frequency histogram for this variable.



C.4.h. Destination

The variable *destination* indicates the final destination of landslide debris originating from the landslide initiation site. The choices include **gully, creek, fan** (in other words a debris fan at the mouth of the gully or canyon), **lake,** or **other.** Following is a histogram for this variable.

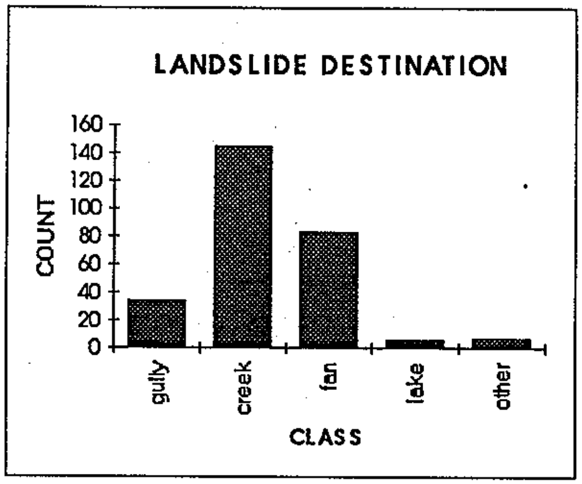

LANDSLIDE DESTINATION
COUNT
160
140
120
100
80
60
40
20
0
gully
creek
fan
lake
other
CLASS

TABLE C-1. Field Data Variable Definitions

HEADER DATA

VARIABLE	FORM NAME	DEFINITIONS
AREA	Area	General area of survey.
ROAD	Road	Logging road name, if known
SEGMENT	Segment	Road segment, integers recorded sequentially
DESCRIPT	Description	General description of site.
DATE	Date	Date data was recorded
KMSTART	Segment - km ______	Chainage of the start of segment in kilometers
KMEND	to km______	Chainage of the end of segment in kilometers
MAPSHEET		Forest Cover Series Mapsheet on which site is located

TERRAIN DATA

TUSMIN	Upslope (°) Min	Minimum slope above the road in degrees
TUSMAX	Upslope (°) Max	Maximum slope above the road in degrees
TDSMIN	Downslope (°) Min	Minimum slope below the road in degrees
TDSMAS	Downslope (°) Max	Maximum slope below the road in degrees
TSCLASS	Soil Class	Soil Class S - Sand; LS - Loamy Sand; SL - Sandy Loam; SCL - Sandy Clay Loam; SC; Sandy Clay; L - Loam; SIL - Silty Loam; SI - Silt; SICL - Silty Clay Loam; CL - Clay Loam; SIC - Silty Clay; C - Clay; HC - Clay
BIOGEO	Biogeoclimatic Subz/Var	Biogeoclimatic Subzone and Variant
TGRAD	Gradation	Soil Gradation P - Poorly; M - Moderate, W - Well, N/A - Not Applicable
TDENS	Density	Soil Density L - Loose; C - Compact, D - Dense; N/A - Not Applicable
TGEN	Genetic Material	Genetic Material in Terrain Unit M - Morainal; C - Colluvial; FG - Fluvioglacial; F - Fluvial LG - Glaciolacustrine; L - Lacustrine; R - Bedrock
TRTYPE	R (Type)	Rock type if bedrock is present
TEXP	Surface Expression	Surface Expression of Terrain Unit B - Blanket; C - Cone; F - fan; H - Hummocky; M - Rolling R - Ridged; T - Terrace; V - Veneer
TDEPTH	Soil Depth	Soil Depth S - Shallow (<50 cm); M - Moderate (51-100 cm); D - Deep (> 100 cm)
TPROSS	Processes	Surface Processes A - Avalanched; F - Slow Slope Failures; R - Rapid Slope Failures; V - Gullied; N - None; O - Other
TSPOS	Slope Position	Slope Position TP - Top; U - Upper; M - Middle; L - Lower; TO - Toe
TSSHAPE	Slope Shape UD	Shape of slope up and down the fall line CV - Concave; CX - Convex; S - Straight
TSEEP	Seepage	Seepage C - Continuous; I - Intermittent; N - None

TABLE C-1 (cont). Field Data Variable Definitions

ROAD DATA

VARIABLE	FORM NAME	DEFINITIONS
RWMIN	Road Width(m) Minimum	Minimum Road Width
RWMAX	Road Width (m) Maximum	Maximum Road Width
RDDMIN	Ditch Depth (m) Minimum	Minimum Ditch Depth
RDDMAX	Ditch Depth (m) Maximum	Maximum Ditch Depth
RFHMIN	Fill Height (m) Minimum	Minimum Fill Height
RFHMAX	Fill Height (m) Maximum	Maximum Fill Height
RCHMIN	Cut Height (m) Minimum	Minimum Cut Height
RCHMAX	Cut Height (m) Maximum	Maximum Cut Height
RFSMIN	Fill Slope (°) Minimum	Minimum Fill Slope
RFSMAX	Fill Slope (°) Maximum	Maximum Fill Slope
RCSMIN	Cut Slope (°) Minimum	Minimum Cut Slope steepness in degrees
RCSMAX	Cut Slope (°) Maximum	Maximum Cut Slope steepness in degrees
RGMIN	Gradient (%) Minimum	Minimum Road Gradient in percent
RGMAX	Gradient (%) Maximum	Maximum Road Gradient in percent
RDCULV	Drain Culverts	Number of drainage culverts within the road segment
RCKCULV	Ck Culverts	Number of creek-carrying culverts within the road segment
RDISTALL	Drain Install.	Quality of drainage installation within segment N - None; P - Poor; F - Fair; G - Good
RDMAINT	Drain Maint.	Quality of drainage maintenance N - None, P - Poor; F - Fair; G - Good
RWOOD	Wood in Fill	Amount of wood observed in fill L - Little; S - Some; D - Dominant; O - Other
RCONST	Const. Method	Road construction method B - Backhoe; D - Dozer, B - Blasting
RPRISM	Road Prism	Type of road prism constructed FB - Full Bench; PB - Part Bench; GF - Gully Fill; CF - Cut-Fill
RMM	M.M. Potential	Subjective estimate of Mass-Movement Potential L - Low; M - Moderate; H - High

TABLE C-1 (cont). Field Data Variable Definitions

LANDSLIDE DATA

VARIABLE NAME	FORM NAME	DEFINITIONS
LSLIDE		Whether or not a landslide was found in this road segment Y=Yes; N=No
LLENGTH	Length (m) =	Average Length of landslide initiation zone
LWIDTH	Width (m) =	Average Width of landslide initiation zone
LDEPTH	Depth (m) =	Average Depth of landslide initiation zone*
LTRAVEL	Travel (m) =	Total Travel distance of landslide debris; top of headscarp to toe of debris
LTYPE	Type	Landslide type DA - Debris Avalanche; DF - Debris Flow; SL - Slump; EA - Earthflow
LHEAD	Headscarp Location	Location of Landslide Headscarp within the road prism or terrain unit. UN - Uniform Slope; HE - Gully Headwall; SI - Gully Sidewall; BE - Bench Face; CU - Road Cutslope; FI - Road Fillslope; SW - Swale or subdued gully
LWATER	Water Type	Origin of water on site GR - Groundwater; SU - surface water; SH - Sheet Flow
LWSOURCE	Water Source	Source Location of water entering the landslide area SP - Spring; CH - Channel/Rill; CU - Culvert; DI - Ditch RS - Road Surface; ? - Unknown
LSTRENGTH	Soil Strength Contribution	Factors which may have reduced the resisting forces or increased driving forces within the landslide U - Undercutting; O - Overloading; F - Fill Rot; R - Root Loss; N - Not Applicable
LDEST	Destination	Ultimate Destination of landslide debris G - Gully; C - Creek; F - Alluvial or Debris Fan; L - Lake
LH2O	H2O Quality	Whether or not water quality may have been affected Y- Yes; N - No
LDATE	Date Occurred	Date landslide is estimated to have occurred
LSOURCE	Source	Source of data on landslide if other than field notes
LXREF	X-Ref	Cross-Reference to other data on this landslide
NOTES	Notes	Miscellaneous notes on the landslide

* usually this dimension was adjusted to make a volume estimate realistic

D. LANDSLIDE HAZARD PREDICTION MODELS - ANALYSIS

D.1 General Discussion

During the early stages of this study, the analysis identified several unique and somewhat different mechanisms were responsible for the instability leading to landslides.

The first mechanism is the result of undercutting of the slope by a road cut. In this case, the loss of mechanical support by the removal of the soil results in collapse of the slope above. This mechanism is particularly predominant in seepage areas.

The second mechanism is the result of overloading of the slope by a road fill coupled with the introduction of diverted water to the fill from a blocked stream culvert in a gully or creek. In this case the water flows out of the channel, onto the road and over the fill slope. The water saturates the fill slope, raises the pore water pressures to a critical level then causes the fill to fail. In this case, the debris often immediately enters a creek channel or gully and continues downslope.

The third mechanism also involves the overloading of the slope by a road fill. In this case, the triggering mechanism is the introduction of water from either the road ditch or the road surface. Usually the water is directed down the road in ruts or rills spilling off the road and onto the fill. Also, sometime the road ditch is blocked by debris sloughing from the road cut, resulting in the diversion of water across the road and onto the fill. As with the second mechanism, fill materials are partially or fully saturated by water resulting in shear failure and the initiation of a landslide.

The forth mechanism involves the initiation of a landslide on a natural slope caused by the diversion of water off a road upslope. In this case water is introduced to a slope where infiltration volumes are normally low. This results in an unusual soil saturation and leads to a landslide.

The fifth mechanism involves purely natural processes unrelated to man's activities.

All of the above mechanisms can be associated with all of the types of landslides inventoried including debris avalanches, debris flows, slumps and earthflows. Following is a summary of the mechanisms described.

MECHANISM		FAILURE LOCATION
1. Seepage or channel water on cut slope	→	Cut slope failure
2. Channel or gully water uncontrolled across road	→	Fill slope failure
3. Ditch water or road surface water diverted across road	→	Fill slope failure
4. Water diverted off road	→	Off-site landslide
5. Natural processes	→	Natural landslide

The landslide inventory database has been subdivided into subgroups according to the above-noted mechanisms. The database variables *headscarp location (LHEAD)* and *water source (LWSOURCE)* have been used as the basis of the subgrouping as shown in the Table D-1. (Definitions of these variables are given in Table C-1).

Table D-1. Variable categories used as the basis of database subgroups

SUBGROUP	*LHEAD*	*LWSOURCE*
1	all	all
2	CU	SP, CH
3	FI	CH
4	FI	DI, RS
5	BE, HE, SI, UN, SW	CU, DI, RS, CH,SP
6	BE, HE, SI, UN, SW	

Data has been subgrouped for both the landslide sites and the adjacent non-landslide sites. The non-landslide sites have been grouped according to the characteristics of the landslide site that is the closest or adjacent to it. Table D-2 show the labels and number of sites associated with each subgrouping based on mechanism and type of site. These database subgroups will be used and/or referred to throughout most of this section as the form the basis for developing hazard predictions models for the specific mechanisms.

Table D-2. Database subgroupings used in developing hazard prediction models.

	All Data	data label	# of sites	*Landslide Data*	data label	# of sites	*Non-Landslide Data*	data label	# of sites
MECHANISMS	All mechanisms	A1	701	All mechanisms	L1	275	All mechanisms	N1	426
	Seepage on cuts	A2	109	Seepage on cuts	L2	27	Seepage on cuts	N2	82
	Channel water on fill	A3	77	Channel water on fill	L3	28	Channel water on fill	N3	49
	Ditch/road water on fill	A4	379	Ditch/road water on fill	L4	121	Ditch/road water on fill	N4	258
	Water diverted off-site	A5	66	Water diverted off-site	L5	29	Water diverted off-site	N5	37
				Natural landslides	L6	70			

TABLE D-3
SUMMARY OF VARIABLE COMPARISONS
LANDSLIDE VS. NON-LANDSLIDE SITES
PROBABILITY VALUES

DATABASE DESCRIPTION		L1/N1 ALL SITES	L2/N2 CUTSLOPES	L3/N3 FILLS-GULLIES	L4/N4 FILLS-DITCH	L5/N5 OFF-SITE
Upslope (degrees)	Ave	0.011	0.004	0.787	0.013	0.342
	Min	0.007	0.003	0.748	0.015	0.406
	Max	0.021	0.006	0.832	0.015	0.295
Downslope (degrees)	Ave	0.000	0.003	0.923	0.000	0.008
	Min	0.000	0.006	0.988	0.000	0.009
	Max	0.000	0.002	0.862	0.000	0.009
Soil Class		0.492	0.234	0.492	0.642	0.835
BioGeo Subzone		0.403	0.773	0.660	0.330	0.504
Gradation		0.102	0.325	0.355	0.875	0.588
Density		0.085	0.577	0.190	0.014	0.248
Genetic Material		0.099	0.303	0.009	0.713	0.610
Surface Expression		0.489	0.843	0.209	0.715	0.612
Soil Depth		0.014	0.035	0.574	0.855	0.240
Processes		0.000	0.000	0.161	0.000	0.008
Slope Position		0.011	0.505	0.598	0.508	0.015
Slope Shape		0.313	0.116	0.795	0.034	0.163
Seepage		0.000	0.020	0.094	0.003	0.983
Road Width (m)	Ave	0.177	0.189	0.724	0.187	0.017
	Min	0.005	0.064	0.254	0.010	0.010
	Max	0.725	0.362	0.188	0.641	0.032
Ditch Depth (m)	Ave	0.080	0.311	0.286	0.114	0.391
	Min	0.177	0.304	0.130	0.279	0.190
	Max	0.062	0.318	0.573	0.091	0.650
Fill Height (m)	Ave	0.000	0.016	0.029	0.000	0.006
	Min	0.000	0.021	0.043	0.000	0.005
	Max	0.000	0.020	0.038	0.000	0.009
Cut Height (m)	Ave	0.000	0.003	0.120	0.008	0.252
	Min	0.001	0.015	0.646	0.020	0.155
	Max	0.000	0.002	0.043	0.004	0.397
Fill Slope (degrees)	Ave	0.126	0.008	0.757	0.015	0.028
	Min	0.076	0.004	0.706	0.002	0.035
	Max	0.201	0.019	0.404	0.076	0.024
Cut Slope (degrees)	Ave	0.574	0.109	0.581	0.118	0.226
	Min	0.929	0.118	0.380	0.245	0.215
	Max	0.385	0.118	0.764	0.081	0.248
Road Gradient (%)	Ave	0.979	0.515	0.004	0.430	0.662
	Min	0.974	0.440	0.002	0.435	0.591
	Max	0.939	0.596	0.009	0.436	0.729
Drain Installation		0.000	0.100	0.043	0.001	0.604
Drain Maintenance		0.001	0.120	0.060	0.017	0.275
Wood in Fill		0.012	0.002	0.806	0.079	0.003
Construction Method		0.763	0.413	0.628	0.393	x
Road Prism		0.600	0.292	0.229	0.270	0.064
Critical Slope Angle		0.000	0.000	0.933	0.000	0.028

NOTE: VARIABLES WITH SIGNIFICANT DIFFERENCES BETWEEN GROUPS ARE SHADED (P < 0.01)

211-TSUM.XLS

terratech WESTERN PROFILE

The data summary sheets for each of the 16 databases described in Table D-2 can be found in Appendix C. These sheets provide the basic statistics including means and standard deviations for the numerical variables such as *cut height* and frequency counts for the categorical variables such as *soil class*. In addition to the standard variables, some derived variables such as *average road width, critical slope angle,* etc. have been compiled in Appendix C. (The definition of the variable *critical slope angle* is illustrated in Section E.2.b).

Detailed histograms and graphs are provided in Appendix D that compare landslide sites with the adjacent non-landslide sites. For example, databases L1 and N1 are compared variable by variable to determine which variables indicate the greatest differences between the two types of sites. The probability values found below each graph is the probability that the given variable is **poor** at predicting whether or not a landslide would occur. The probabilities have been calculated using t-test and chi-square tests for numerical and categorical variables respectively.

Table D-3 summarizes the probability values found in Appendix D for each of the 44 variables for each type of landslide mechanism. The shaded probability values indicate variables that have some predictive capability for the given landslide mechanism. These values are discussed in the following sections.

D.2. Analysis of All Landslide Mechanisms Combined

D.2.a. General

The entire data set was first analyzed together to determine what factors seem to be influencing landslides in general in the region. By examining the Table D-3, it can be seen that of the 44 variables analyzed, 16 have some predictive capability. The significant terrain variables include *natural upslope angle, downslope angle, slope process,* and *seepage.* The significant road-related variables include *road width, fill height, cut height, drainage installation, drainage maintenance,* and *critical slope angle.* Each of these variables is discussed below.

D.2.b. Terrain Variables

The natural upslope and downslope angles were found to significantly influence landslide occurrence as one would expect. The average natural slope at landslide sites was found to be 31.8° while at the adjacent non-landslide sites, the average slope was found to be 28.5°. While this difference of 3.3° may seem to be minor, this is more significant when considering the 701 sites this data represents. It should be noted that a larger difference may be found if non-landslide sites further removed from the landslides (perhaps with more gentle terrain) were included.

The *slope process* variable may be significant because of the large number of landslide sites identified as experiencing rapid failures. However, because this variable actually reflects landslides caused by roads, it cannot be used as a predictor.

The *seepage* variable indicates a higher incidence of landslides in areas of continuous and intermittent seepage than for non-landslide sites, as one would expect (see histogram in Appendix D). This is due to the fact that seepage areas are more likely to saturate and destabilize road disturbances.

The other variables inventoried do not successfully distinguish landslide sites from adjacent areas that did not slide.

D.2.c. Road-related Variables

The variable *minimum road width* is found to be weakly related to landslides. Landslide sites are found to be associated with an average minimum road width of 5.3 m while adjacent non-landslide sites have an average minimum width of 5.7 m. After some review, it was determined that the primary reason for this correlation is the fact that many fill-slope related slides have actually resulted in a narrower road (part of the shoulder has failed). This should therefore be considered a trivial correlation.

The variable *fill height* appears to be strongly related to landslide occurrence. Landslide sites are found to have an average fill height of 5.7 m while the adjacent areas had an average height of 4.3 m. This trend makes mechanical sense as the higher fills will likely result in greater shear stresses. One should be cautioned by the fact, however, that fill height is geometrically correlated to both terrain slope and fill slope. Therefore, much of the predictive capability of the variable may be associated with slope, rather than fill height. The multivariate CHAID analysis is able to test for this and arrives at the same conclusion for this data set.

The variable *cut height* is also related to landslide occurrence, with an average value of 5.8 m for landslide sites and 4.2 m for non-landslide sites. These values are similar to those for *fill height*. Again, much of the predictive capability of the variable can be explained by its geometric correlation to *natural terrain slope* and *cut slope*.

The variables *drainage installation* and *drainage maintenance* were both found to be factors in landslide occurrences. With *drainage installation*, a larger percentage of sites are associated with landslides in the "none" to "poor" categories as shown in Table D-4. This indicates that areas immediately adjacent to landslide sites might have had somewhat better provisions for handling drainage, and that the lack of it results in more landslides.

The variable *critical slope angle* which is the average of the *terrain downslope* and the *fill slope angle* (see Section E.2.b) is highly correlated with landslide occurrence. For landslide sites, the average *critical slope* is 36.8° while for adjacent sites it is 33.6°. This supports the general observation that steeper fills on steeper slopes cause more landslides.

An even greater difference in the average slopes is found at sites at and adjacent to fill-slope failures caused by ditch and road-surface water (37.9° vs 34°, difference = 3.9°).

Table D-4. Percentage of sites associated with landslides within the four categories of the variables *drainage installation* and *drainage maintenance.*

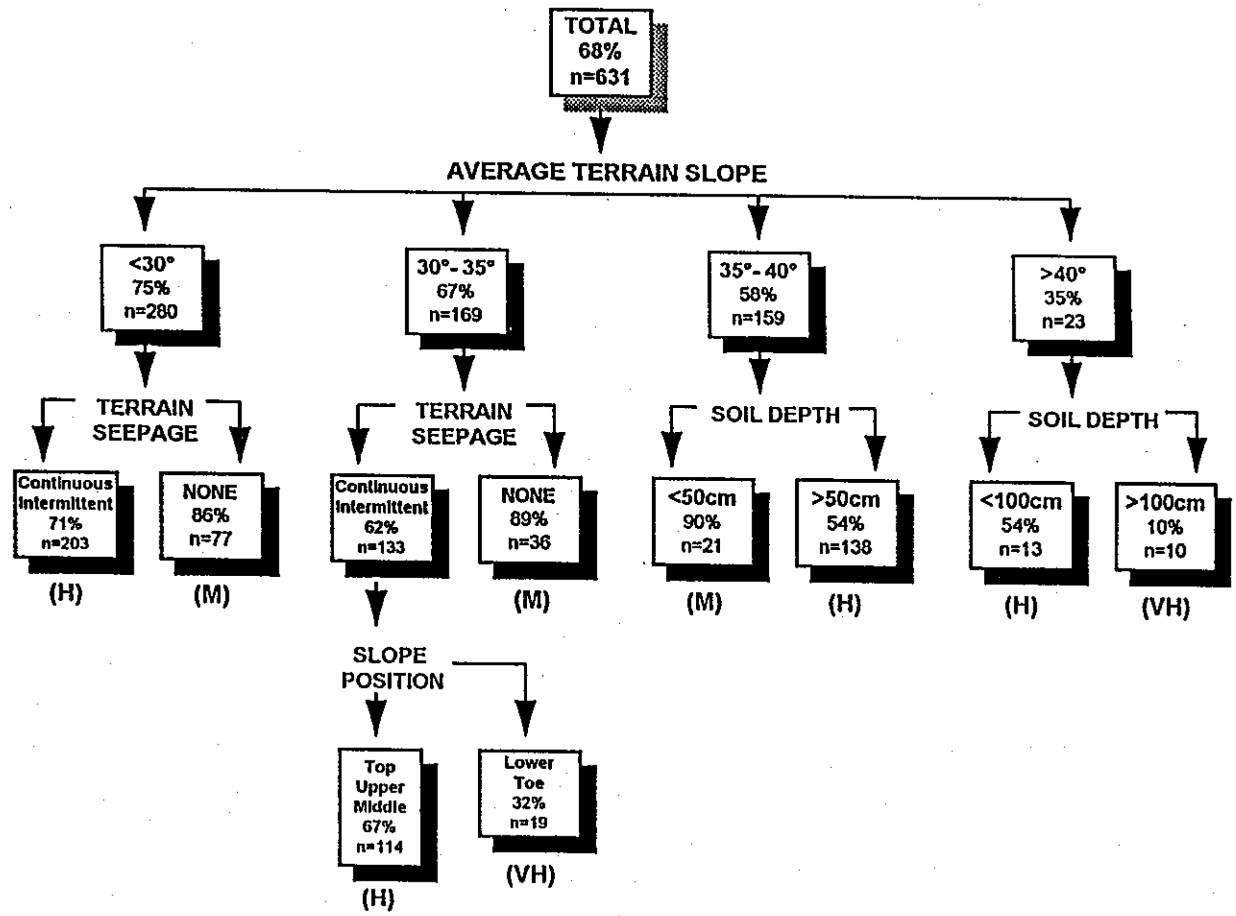
	DRAINAGE INSTALLATION			
	NONE	***POOR***	***FAIR***	***GOOD***
Number of Sites	185	138	249	35
% Landslide	38%	37%	22%	11%
	DRAINAGE MAINTENANCE			
Number of Sites	254	184	147	22
% Landslide	34%	35%	18%	14%

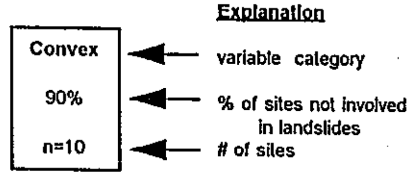
D.2.d. Variable Interrelationships

A multivariate CHAID analysis has been completed which explores the interrelationships of the variables and identifies the combinations that lead to the greatest distinction between landslide and non-landslide sites. The details of this analysis are found in Appendix E. The results are presented in the form of a tree diagram that allow the classification of a given site into a hazard category given certain characteristics at the site. Only the most predictive variables are used in the tree diagram. Figure D-1 shows the results of the analysis for terrain variables only. As can be seen, the important variables are *average terrain slope, seepage, soil depth,* and *slope position.* Note that the variable *soil depth* and *slope position* were not found to be good predictors when isolated. However, when analyzed within certain categories of the variables *terrain slope* and *seepage,* they provide added insight.

Each box in the tree represents a group of sites. The uppermost box indicates the total sample of 631 sites (70 sites of the 701 have no road data) of which 68% are **not** associated with landslides. Moving down the tree, the variable *average terrain slope* has 4 categories, <30°, 30°-35°, 35°-40°, and >40°. Each of these categories has a certain number of sites associated with them. In the category <30° there are 280 sites, 75% of which do **not** have landslides. In this manner, one moves down the tree, choosing the categories that apply to the given site until one reaches the end of a branch. The box at the end is then used to determine the relative hazard of this site relative to the landslide inventory data. For example, say a site has the following terrain characteristics: *average terrain slope* = 33°, *seepage* = continuous, *slope position* = lower. By following the tree diagram to the end of the branch it is found that 19 sites in the landslide inventory fit within these categories, only 32% of which were **not** associated with landslides. This represents a much above average chance of experiencing a landslide. As seen in Figure D-1, this box has been labeled (VH) to indicating a much higher percentage of landslides associated with this small group of sites.

FIGURE D-1
CHAID TREE FOR LANDSLIDE HAZARD RATING
USING ONLY TERRAIN CHARACTERISTICS
ALL LANDSLIDE MECHANISMS





slide: LANDSLIDE 1A
file: 211-01a.ppt

Figure D-1 represents the combination of variables and categories that has the best chance of finding data subsets that have very high or very low percentages of landslide sites. However, because it does not take into account road-related variables, there are a number of results with mediocre percentages (50-80%). Figure D-2 uses the tree given in Figure D-1 and adds to it road related variables. In this tree, the road-related variables are shown with grey shadows while the terrain variables have black shadows. As can be seen, this tree is more complicated, but does a better job of giving very high or very low percentages. For example, the following characteristics: *average terrain slope* = <25°, and *seepage* = none results in a subgroup of 38 sites, 95% of which are not associated with landslides. On the other hand, the characteristics: *average terrain slope* = 35°-40°, *soil depth* = >50 cm, *average cut height* = >10m results in a subgroup of 10 sites, all of which involve landslides.

By mixing terrain and road-related variables together, a more complicated but more predictive tree results. Figure D-3 shows the best predictive tree that could be generated by the CHAID methodology from the total data set. The tree results in 13 classifications, 5 of which are much more hazardous than average (VH), 3 of which are more average (H), and 5 of which are less hazardous than average (M). In this case "average" is considered the norm for the entire data set, i.e. 68% of the sites not being associated with a landslide. Because this study focused on landslide cluster areas, this "average" is considered to have a high (H) overall hazard rating.

The significant variables in predicting the relative hazard of a particular road segment are found to be: *critical slope angle, average cut height, average fill height, drainage installation, seepage, slope position, slope shape,* and *average terrain slope.*

D.3. Analysis of Sites Associated with Cut Slope Failures

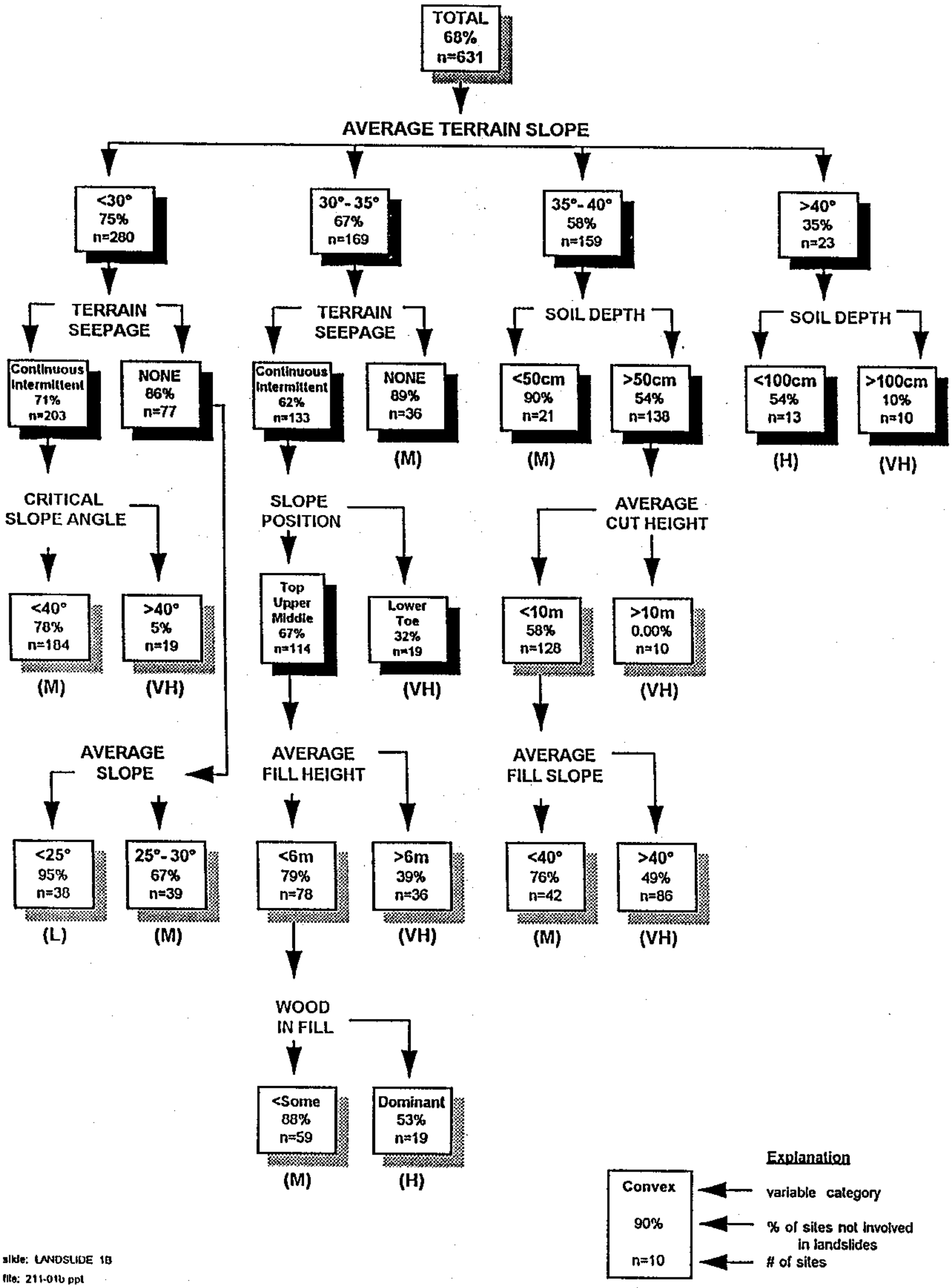
D.3.a. General

Table D-3 (L2/N2) indicates that of the 44 variable analyzed, 13 (including minimums, maximums and averages) were found to have some predictive capability for cut-slope related failures. When analyzed individually, the significant terrain variables include *natural upslope angle, natural downslope angle,* and *slope process.* The significant road-related variables include *cut height, fill slope, wood in fill,* and *critical slope angle.*

D.3.b. Terrain Variables

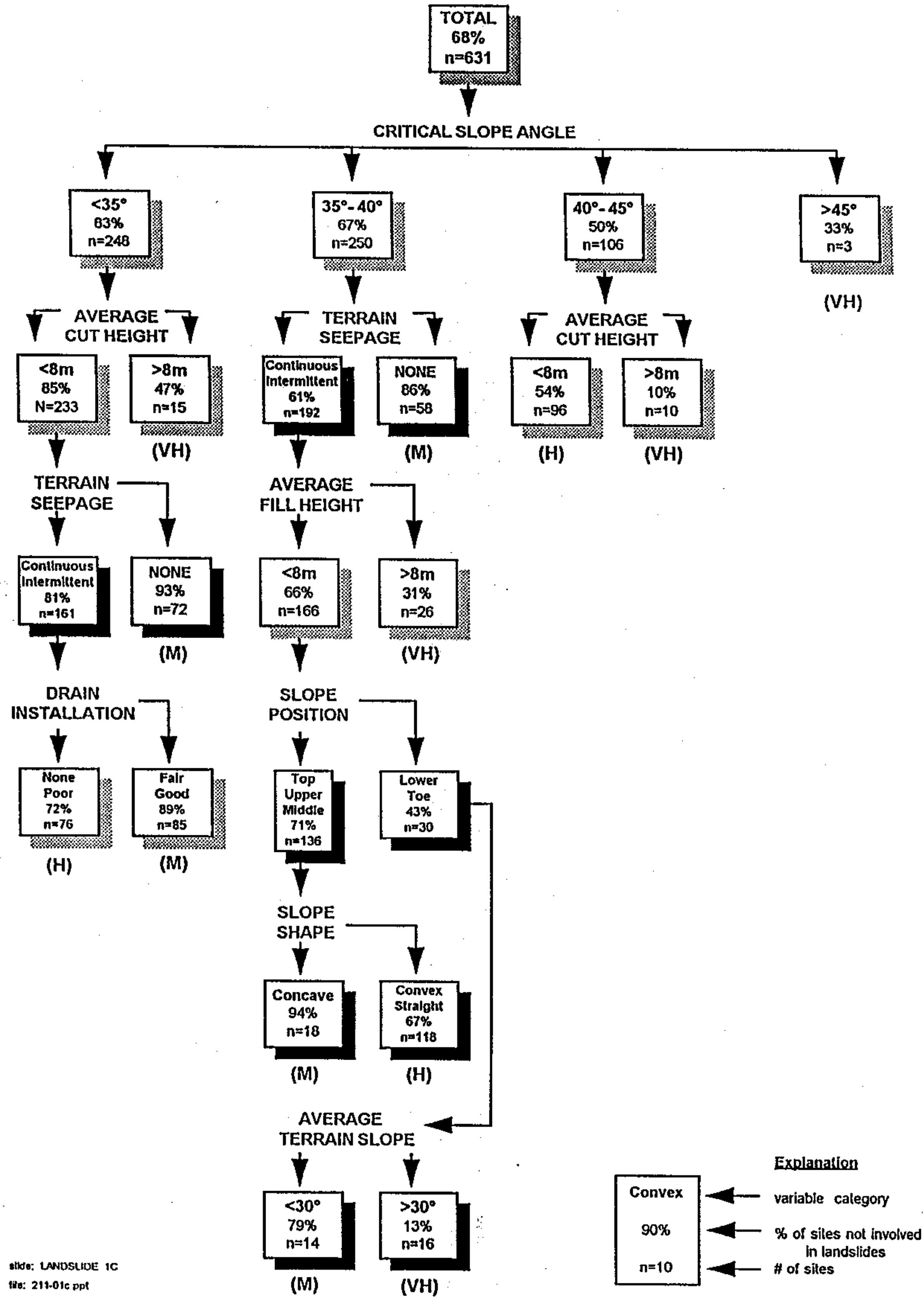
The natural slope angle of the terrain, both upslope and downslope, is found to be the most significant predictor. For landslide sites, the average upslope and downslope angle is found to be 33.7° and 32.3° respectively (Appendix C). For adjacent non-landslide sites, the average upslope and downslope angles are 29.0° and 27.7° respectively, a difference of between 4° and 5°. This is an intuitive result as one would expect that steeper slopes would be more susceptible to landsliding.

FIGURE D-2
CHAID TREE FOR LANDSLIDE HAZARD RATING
USING TERRAIN AND ROAD CHARACTERISTICS
ALL LANDSLIDE MECHANISMS



slide: LANDSLIDE 1B
file: 211-01b ppt

FIGURE D-3
CHAID TREE FOR LANDSLIDE HAZARD RATING MIXED ROAD AND TERRAIN CHARACTERISTICS ALL LANDSLIDE MECHANISMS



slide: LANDSLIDE 1C
file: 211-01c ppt

The only other terrain variable found to be statistically predictive is *slope processes*. Unfortunately, for the reasons expressed in Section D.2, this variable cannot be used in hazard prediction modeling.

D.3.c. Road-related Variables

The variable *cut height* was found to be directly related to the incidence of cut-slope failures. At landslide sites, the *average cut height* was found to be 8.5 m. At non-landslide sites, it was found to be 4.6 m, almost half the height at landslide sites. Part of the reason for this may be that at failed road sections, the actual cut height prior to failure may be obscured. For this reason, some cut heights may be overestimated. However, it is expected that on steeper slopes, larger cuts would result in the destabilization of more of the upslope area.

It is significant to note that the variables *fill slope angle, wood in fill* and *critical slope angle* are correlated with the incidence of cut slope failures. Though there is no obvious physical connection, it is possible that cut slope failures have tended to occur in areas where steep slopes have resulted in steeper than average fills. These fills may also have required more stump and log reinforcement. Critical slope angle, by definition, is associated with natural slope angle. Regardless of the reason, these three variables are likely associated with natural slope angles and have been purposely excluded from further analysis.

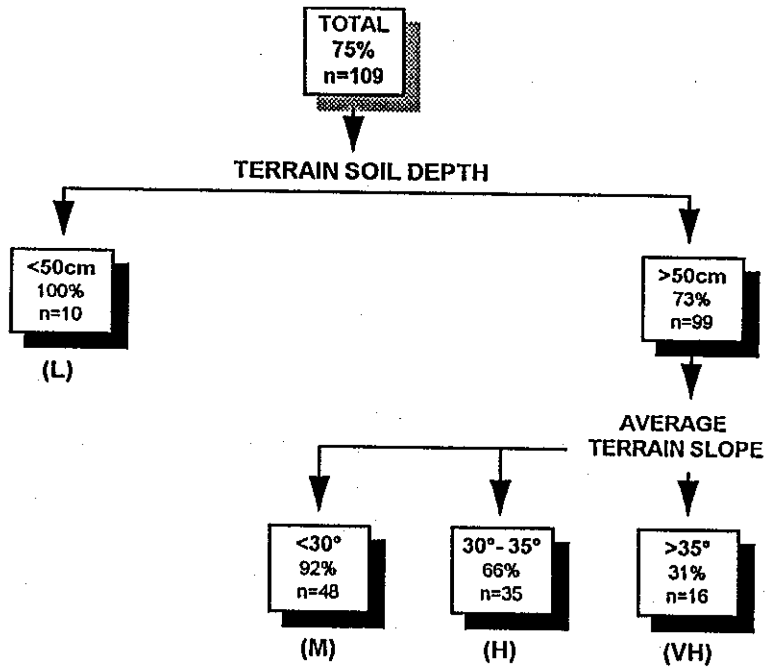
D.3.d. Variable Interrelationships

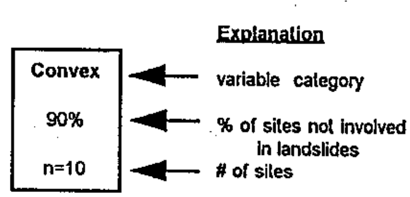
A multivariate CHAID analysis has been completed for the L2/N2 data subset associated with cutslope failures. An explanation of the interpretation of CHAID diagrams is given in Section D.2.d. Figure D-4 shows the results of the analysis for terrain variables only. It is found that, in combination, the two variables *terrain soil depth,* and *average terrain slope* formulate the entire prediction model. It is found that, out of 109 sites, 10 were cataloged in the vicinity of cutslope failures with soils less than 50 cm deep. Of these 10 sites, none were associated with landslides. This makes sense as cuts in rock would definitely be more stable.

Given the soil is greater than 50 cm deep, the tree indicates that the *average terrain slope* variable is the most significant (*average slope = (upslope + downslope)/2*). The categories <30° and >35° indicate below average and above average landslide potential respectively. The 35 sites that fall into the middle category (30°-35°) is somewhat average, i.e. similar to the total sample with respect to the percentage of sites not associated with cutslope failures.

To further enhance the prediction model, road related variables have been included as shown in Figure D-5. This classification tree adds the variables *drainage maintenance* and *average cut height* to the analysis. From the 30°-35° *average terrain slope* variable, the tree splits off a branch with below average hazard associated with fair to good road drainage maintenance. It then splits off an above average hazard branch associated with road cuts >6m high.

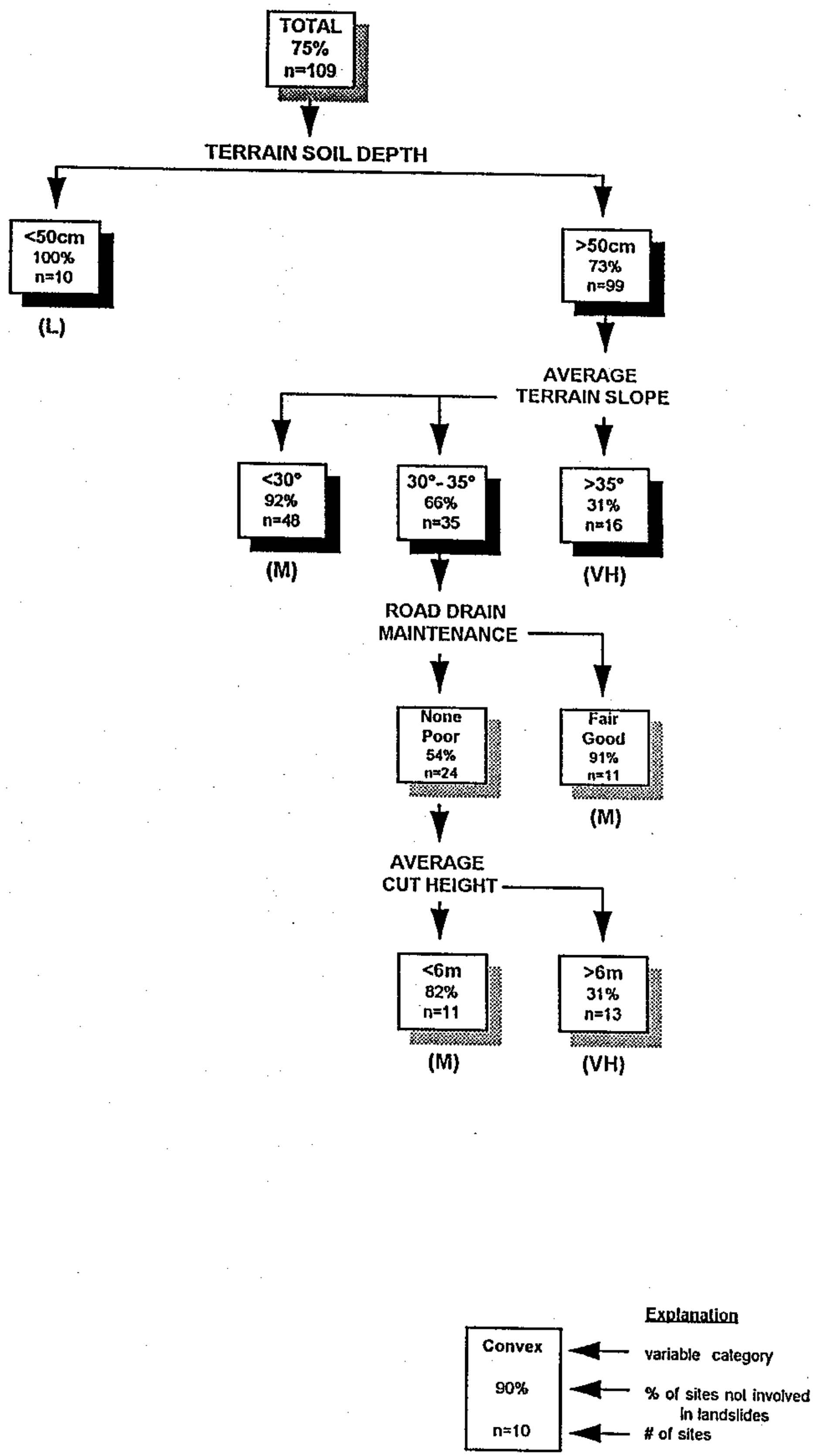
FIGURE D-4
CHAID TREE FOR LANDSLIDE HAZARD RATING
USING TERRAIN CHARACTERISTICS
CUTSLOPE FAILURE MECHANISM ONLY





slide: LANDSLIDE 2C-1
file: 211-02c1.ppt

FIGURE D-5
CHAID TREE FOR LANDSLIDE HAZARD RATING
USING BOTH ROAD AND TERRAIN CHARACTERISTICS
CUTSLOPE FAILURE MECHANISMS ONLY



slide: LANDSLIDE 2C
file: 211-02c.ppt