LANDSLIDE INVESTIGATION IN COASTAL BRITISH COLUMBIA: A DISCUSSION OF CAUSE AND EFFECT

by

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ABSTRACT: Landslide investigations are complex and usually have multiple objectives. A thorough investigation must focus not only on the conditions at the initiation site that contributed to the landslide – "cause" - but also on the "effects" to downslope / downstream resources. Often one initiation mechanism cannot always be established with certainty. The effects of the landslide must be compared to nearby ongoing geomorphic processes, and may require investigation by a multidisciplinary team of specialists.

A systematic, field-based method for the investigation of landslides is discussed. This method links direct visual evidence on site to contributing factors and possible initiation mechanisms as a means of determining "cause". A similar approach to the assessment of "effect" is also discussed, with reference to the downslope / downstream resources and the geomorphic processes in the area.

KEY WORDS--Landslide investigation, observational techniques, forestry-related landslides, forest road, clearcut landslides, mass-wasting geomorphic processes, environmental litigation

BACKGROUND

Landslides are one of the more common forms of adverse "environmental effects" associated with forest road construction and forest harvesting activities. Many recent changes to forest practices are associated with reducing the likelihood of landslides following forest road construction and harvesting. For example, within the British Columbia Forest Practices Code (FPC) introduced in 1995 there are legislated requirements for road planning, assessment, design, construction, maintenance, and deactivation (storm-proofing or complete deconstruction). Similarly, there are legislated requirements for terrain stability assessments of proposed clearcut harvesting areas and gully systems. Additional FPC Regulations and other legislation (such as the Canadian Federal Fisheries Act) provide for penalties and/or criminal charges if a forestry-related landslide occurs and results in damage to fish habitat. Much of the legislation relating to landslides associated with forestry activities is linked to the downslope / downstream effects of the landslide, rather than the actual initiation of the landslide. Increasing emphasis has also been placed on landslide assessment for worker safety (BC Workers Compensation Board, 1998; BC Ministry of Forests, 1997) including upslope areas above forestry operations.

Despite this emphasis on landslide prevention and the penalties for landslide occurrence, there is some possibility of a landslide related to almost all forestry activities in mountainous terrain. Unrecognized landslide-prone terrain, inappropriate road design and/or construction, lack of maintenance, and/or inadequate deactivation, combined with local storm activity, can result in a landslide. When a landslide occurs, an investigation is commonly carried out to determine if damage to the environment has occurred or any legislated requirements have been contravened. A geoscientist or geotechnical or geological engineer is often required to determine the cause(s) of the landslide, as well as its downslope/downstream effects.

An objective, field-based observational method is essential for such an investigation. The method must consider the safety of workers who carry out mitigative actions, any applicable regulations, the required standard of road construction and harvesting requirements at the time of forest operations, and the limited resources usually available to carry out such an investigation. A thorough investigation of a landslide requires a familiarity with the local terrain conditions, an understanding of forest road construction and harvesting practices, in addition to a broad knowledge of geotechnics and geomorphology.

This paper reviews methods of carrying out landslide investigations. The basic approach is to document site observations, and logically link these observations to factors that may have contributed to the landslide. Once the contributing factors have been identified, an initiation mechanism can be often inferred. Assessment of the downslope/downstream effects of a landslide are critical to determine if the landslide can be categorized as damage, or simply a change, to downslope/downstream resources.

Although this approach may seem obvious, "many things may appear obvious, but unless they are spelled out, they may not appear obvious to many" (Anon).

OBJECTIVES

A landslide investigation should include both the initiation site and downslope areas. For the initiation site, the investigation may have the following objectives:

- to determine the contributing factors, the initiation mechanism and identify the cause(s);
- to determine the contributing factors to improve future forest practices
- to evaluate the stability of the site for safety for: emergency response (where

needed); landslide mitigation work; public use and/or continuing forestry operations.

Similarly, an investigation of the downslope/downstream effects of the landslide may have the following objectives:

- to document the geomorphic consequences;
- to assess the extent of environmental change or damage, if any;
- to develop a mitigation plan to minimize damage to resources.

FIELD ASSESSMENT

Investigation of the cause of a landslide commonly involves aerial and ground assessment of the headscarp area, as well as the terrain above the headscarp. Often a review of the road construction and/or logging plans is beneficial, as well as an inspection of surrounding areas to determine the characteristics of logging practices. A review of air photos and previous experience in the area is very helpful to determine the extent of geomorphic processes on the surrounding hillslopes. Site observations adjacent to the headscarp can be invaluable to infer the hillslope conditions prior to the landslide.

Similarly, the investigation of landslide effects involves the assessment of the transportation and deposition zones along the landslide track. During the assessment, it is important to document both the conditions along and adjacent to the landslide track. The latter can be useful to infer the site conditions prior to the landslide.

Limitations of the field assessment are related to its empirical, observational nature and the timing relative to the landslide. Often the assessment is carried out several days to months following the landslide. Investigators must be cognizant of changes that can occur at the site resulting from groundwater seepage, erosion of the failure plane, ravelling of the headscarp area, vegetation growth, and forest maintenance operations both in the headscarp area and along the roads above. The safety of the landslide investigators often precludes an immediate assessment of the landslide area.

It should be noted that during the field assessment, it is often possible to gather more detailed information than can be observed during a pre-construction or pre-harvesting assessment. Such information can include:

- depth to impermeable or stable strata;
- as-built roadcut and roadfill geometries;
- as-built road grades and drainage;
- soil strength properties.

ASSESSING POSSIBLE CAUSE

The cause of a landslide is usually the combination of several contributing factors, although in some cases it may be possible to identify a single contributing factor. Contributing factors are spatial and temporal site characteristics that reasonably increased the possibility of the landslide. The initiation mechanism is the geomorphic process that likely initiated the landslide, and can only be identified with certainty in a limited number of cases.

Several methods can be used to determine contributing factors, initiation mechanism(s), and the possible cause(s) of a landslide.

Direct visual evidence - Direct evidence observed on site is the most compelling data to identify a potential contributing factor.

Tables 1 and 2 summarize observational evidence and contributing factors for numerous landslide initiation mechanisms: Table 1 for landslides that occur outside the road prism (such as clearcut harvesting landslides); Table 2 for those that occur within the road prism (such as roadfill landslides). Familiarity with forest road construction and harvesting practices and local terrain conditions is important to determine the contributing factors and cause(s) of any landslide associated with forestry operations.

General area evidence - Information from the surrounding area can help determine the contributing factors. Such information can include identification of the natural geomorphic processes in the area, as well as the response of logging and road construction in similar terrain as the landslide under investigation.

Inspection of the general area can give some indication of the types of landslides that are common to the area. For example, in some areas gullied terrain may be unstable following harvesting; in other areas because of differences in soils and climate, gullied areas can be quite stable following forest harvesting. An inspection of the general area This information can be useful to identify forestry practices that may have contributed to the landslide.

Determining the amount of rainfall in the general area at the time of, and prior to, the landslide is very helpful but can be difficult unless the forestry crew on site is keeping a daily rainfall record. Rainfall intensity has been shown to be highly variable across an advancing front for coastal storms, with small cells of intense rainfall located within the front (Church and Miles, 1987).

Areas that have experienced landslides following road construction and harvesting may indicate that changes are needed in the local area to improve forest practices. Conversely, the proven stability of similar surrounding areas following forest activities can demonstrate that forestry practices are adequate to prevent landslides.

Inferences from general knowledge and theory - The decreased stability following clearcut logging and sidecast road construction are well documented in academic literature. The applicability of any theory to a landslide site, however, must be made with caution. Often, the research upon which the theory is based is limited by topography, geology, geography, or other regional conditions, and the results of the research may not be applicable to the investigation site.

As an example, windthrow (blowdown) is often thought to be a contributing factor to landslides. However the authors are not aware of any research that has clearly linked windthrow and landslides. Landslides have been occasionally observed in areas of extensive windthrow, however, not all windthrow causes landslides. There are frequently small patches of windthrow or individual windthrown trees in areas of marginally stable terrain, yet no landslides have occurred. One possible explanation is that terrain conditions that predispose a site to landslides are similar to those that predispose a site to windthrow. These conditions are typically steep slopes with shallow soils, and/or wet (poorly drained) soils. Also, intense rainstorms, which tend to trigger landslides, are commonly accompanied by high winds so that windthrow at the landslide site may occur coincidentally.

Table 1. Common possible causes of landslides (outside road prism).

Initiation Mechanism	**Typical Contributing Factors (Causes)**	**Common visual evidence on site**
Water Concentration	road drainage	• culvert directly above headscarp • cross-ditch directly above headscarp • uncontrolled road drainage; erosion of road surface evident. (Note: evidence of surface flows must be visible from the road surface to the headscarp. It is often important to define the length of road or contributing drainage area for individual landslides.)
	yarding disturbance	• erosion of yarding tracks following harvesting; may be dependent on yarding system (more common with high-lead systems) • re-routing of natural creek channels to headscarp
Loss of Toe Support	erosion below at base of slope	• retrogressive-type landslide • stream erosion evident at base of landslide (stream escarpments, gully sidewalls)
Loss of soil mantle strength	root deterioration (after clearcutting)	• failure surface (surface of separation) within depth of rooting, and roots have had time to deteriorate (minimum 1 year since falling)
	root strength loss (after windthrow)	• area of extensive and intense windthrow • can occur soon after (or immediately following) windthrow
	root strength loss (wildfire)	• area of extensive dead trees from wildfire
High pore water pressures	groundwater seepage	• fractured bedrock structure • topography indicates groundwater recharge area
	rain-on-snow event; rapid spring meltwater from snowpack	• relatively continuous snowpack; increased snow accumulations in cutblock relative to unlogged areas • warm rain and warm wind • snow surface exposed to wind (clearcut area)
Gully channel bed mobilization	high water flow (no blockages)	• headscarp of debris flow is isolated from any headwall or sidewall landslides • the high water mark is relatively consistent along the channel above the headscarp
	high water flow (sediment / debris blockage)	• headscarp of debris flow is isolated from headwall or sidewall failures • ponding evident immediately above initiation point • blockage inferred from: conditions in gully channel above; nearby channels; logging method
	moderate to high water flow debris slide or rockfall into channel	• clear connection between debris slide / rockfall and gully channel • evidence of sediment and woody debris storage in the channel upstream

Table 2. Common possible causes of landslides (within road prism).

Initiation Mechanism	Typical Contributing Factors (Causes)	Common visual evidence on site
Fillslope Saturation	seepage zone	• Excessive seepage evident at headscarp
	road drainage	• Inadequate (undersized or too few) road drainage • Capture and rerouting of surface water to headscarp area • Low point in road grade and evidence of excessive water movement along road • Culvert (at headscarp or above headscarp) is blocked with woody debris or sediment • (Note: road drainage that leads to roadfill failure commonly shows evidence of ponding on road surface).
	Inadequate road deactivation	• too few crossditches - surface and subsurface flow is concentrated at marginally stable hillslope / roadfill locations • failed ditchblocks (ditchplugs) at cross-ditch or culvert locations
Loss of Soil Mantle Strength	failure of woody debris supporting roadfill	• remnants of broken, rotting, woody debris (large enough to provide structural strength to roadfill) along sides of headscarp
	root strength loss	• failure surface in or near rooting zone, and stumps buttressing roadfill are evident nearby
	loss of toe support (cutslope)	• cutslope is part of initial failure surface • height of cutslope is significant relative to length of failure surface
	loss of toe support (roadfill)	• culvert erosion at toe of roadfill • stream erosion at toe of roadfill • debris flow erosion at toe of roadfill
Overloading of soil mantle	oversteepened roadfill	• headscarp is located entirely in roadfill • marginally stable terrain below road prism
	excessive roadfill spoil (overloading)	• headscarp is partially located in undisturbed soil mantle • large amount of fill placed for road or landing, relative to nearby areas
	combined oversteepened and overloaded slopes	• headscarp is located in both roadfill and undisturbed soil mantle • roadfill immediately adjacent to headscarp is oversteepened
Gully channel bed mobilization	inadequate drainage	• erosion on road grade at gully crossing • gully channel loaded with sediment and woody debris (based on conditions upslope of road, or road construction method)

Analytical Techniques - Slope stability analysis and simulation modelling have long been used by geotechnical engineers to assess slope stability. On forested hillslopes, the use of the infinite slope stability model LISA (Hammond et al, 1992) has been used to assess of relatively uniform soil layers overlying an impermeable, stable basal unit (such as bedrock or dense till). As discussed in VanDine (1997), the variability over the site can preclude the use of an analytical model, or at least require the results to be interpreted with caution. For the back-analysis of landslide events from roadfills or roadcuts, however, deterministic analysis can assess the relative importance of contributing factors relating to the initiation of the landslide. Since in most cases it is not possible to accurately know all of the variables needed to calculate the results of the model, it is often not possible to accurately determine the absolute importance of a contributing factor in the initiation of the landslide.

Geo-Speculation - Speculation using improbable theories or unsupported rationale, with little direct supporting evidence, has been used to determine landslide cause in some instances. We discourage unsupported speculation on the cause of a landslide, since it cannot withstand the close scrutiny of colleagues. Examples of geo-speculation might include the following conclusions:

- Logging in the valley has changed the local climate, and thus caused a landslide in an unlogged part of the watershed.
- Logging some distance upslope may have affected the unlogged slope below in some undetermined manner, causing a landslide.

Summary - Various methods are commonly used to assess the contributing factors and the possible cause(s) of a landslide. Direct visual evidence is the best method. Inferences regarding the relative terrain and stability conditions, and influence of forestry practices can be made from surrounding logged hillslopes. General knowledge and theory, as well as analytical techniques, can provide background information. Such inferences should be made only after considering the applicability of the knowledge, theories, or analytical techniques relative to the site location.

ASSESSING POSSIBLE EFFECTS

The most visible effects of a landslide on downslope / downstream resources are often the geomorphic consequences of the landslide. Geomorphic consequences are best described as the end result of the landslide process and usually include the following:

- current stability of the headscarp;
- the shape and area (dimensions) of the transportation and deposition zones;
- the depth of soil entrainment in the transportation zone
- the amount and type of soil/bedrock that remains in the transportation zone; and
- the volume of debris (fine sediment, coarse sediment, and woody debris) that is delivered to the deposition zone.

To investigate possible landslide effects it is often necessary to determine the effect on each resource at risk downslope/downstream of the initiation site. Preliminary investigations can lead to more detailed investigations that may involve a multi-disciplinary team. For example, a roadfill landslide which reaches fisheries habitat require assessment by a geotechnical engineer, a soil scientist, a forester, a fluvial geomorpholgist, and a fisheries biologist. Investigation of the effects of a landslide should also consider of options for mitigation and rehabilitation of the landslide area to prevent further damage and to repair existing damage, where practicable.

Direct Visual Evidence - Visual evidence at the landslide site is the most important means of investigating the effects of a landslide. Evidence such as the spatial extent of soil removal along the landslide track, the location of the deposition zone relative to downslope resources, as well as the material in the deposition zone are critical in assessing the effects.

Change or Damage? - Landslides are natural processes in coastal watersheds result in many changes to the environment. Some changes are not likely to be significant (such as the change in the micro-climate on the landslide track), while other changes can be significant. Many of these significant changes involve damage, (i.e. harm or injury, or impairing the function of a resource). Examples include damage to structures or the loss of fish habitat. However, landslides may also have positive effects, such as increased supply of material which is beneficial or needed for fish habitat, wildlife forage, or improved forest productivity in the deposition zone. The extent of change or damage will vary for each downslope / downstream resource in question.

It is also important to consider both short and long term effects when determining the extent of change or damage. A starting point to determine the long term effects may be to assess the change that has occurred, and estimate the likelihood of recovery for the ecosystem to recover if it is impaired. Understanding the significance of the landslide relative to the surrounding environment is critical to understanding the long term effects of a landslide. Such assessments are beyond the scope of engineering or geoscience.

The extent of damage to a resource depends on the severity of the landslide and vulnerability of the resource(s) at risk (BC RIC, 1996). The severity of the landslide depends on a combination of the size of the landslide (magnitude) and its travel distance relative to the resource. The vulnerability of a resource can be subdivided, where appropriate, into spatial vulnerability, temporal vulnerability, and life vulnerability (Morgan et al, 1992). This can help determine the effect on the resource and/or determine possible options for mitigation of the landslide (Wise and VanDine, 1998).

General area evidence and knowledge - Investigation of effects should include an assessment of the geomorphic processes in the watershed, as well as the historical frequency of landslides and wildfire. A landslide in an area with very active processes (steep creeks, snow avalanches, and numerous natural sediment sources) can have much less effect than in a watershed which is inactive. A review of unlogged areas may provide some information relating to the natural landslide frequency, as well as how ecosystems have recovered. Similarly, the landslide history of a watershed may reveal that a watershed has an increased sensitivity to landslide events due to cumulative effects, or there may be beneficial effects due to fluvial processes which depend on the influx of sediment and woody debris for developing the complexity of stream systems. In a watershed with recent large disturbances such as wildfire, a single landslide may contribute an insignificant amount of sediment to a stream compared to erosion processes.

Inferences from theory and analytical techniques - Theories of geomorphic processes and analytical techniques can provide some useful information regarding the landslide effects. Theories can assist in placing the effects of the landslide in context with the surrounding geomorphic processes. Analytical techniques, such as simulation of stream processes, can provide insight into the response of a stream system to the deposition of material following a landslide. However, as noted for landslide initiation, caution is needed to determine the applicability of such models to the site.

More commonly, however, the investigation of landslide effects can provide valuable information regarding possible effects of future landslides. Measurements of the landslide geomorphic consequences can be the basis for the development of empirical or semi-empirical models to predict landslide size and travel distance (such as Wise, 1997) or to test existing models (such as Hungr, 1995). The development of these models is critical to improving the assessment of effects from potential landslides.

Mitigation and rehabilitation - The mitigation and rehabilitation of landslide effects may be warranted to reduce the existing or potential damage of the landslide, and should be part of any landslide investigation. Plans for mitigation and rehabilitation should address all the resources that are, or could be, affected by the landslide. Some common mitigation and rehabilitation factors are shown in Table 3.

STANDARD OF PRACTICE

During a landslide investigation, the following may be reviewed: the appropriateness of the pre-logging stability assessment; the road location, design, and construction practices; and harvesting practices. It should be remembered that the standards of stability assessments, forest planning, as well as road construction and harvesting practices are continually improving. It is important for landslide investigators to be aware of the legislative requirements, assessment techniques, and forest practices that were in place at the time the area was developed.

SUMMARY

Landslide investigations are commonly carried out to determine the contributing factors, possible initiation mechanism(s), and the geomorphic effects on downslope/downstream resources. Direct observational evidence provides the best rationale for the presence of a contributing factor and inferring a possible initiation mechanism. Assessing the effects of the landslide requires examination of the transportation zone and surrounding areas, as well as the deposition zone. Such effects must be assessed in the context of existing geomorphic processes to determine if they represent a change or damage to downslope/downstream environments.

Investigations of landslide sites are carried out with several possible objectives. While such an investigation may be done in association with potential litigation, the data from landslide sites is valuable in future assessments of downslope / downstream risk associated with forestry operations in

Table 3. Common possible effects of landslides (adapted from B.C. Ministry of Forests, 1993 and BC Resources Inventory Committee, 1996).

	Possible Effects or Damage	**Common visual evidence on site**	**Common factors for mitigation and repair / rehabilitation**
Social Resources			
human life	• loss of life	• track extends to work area, or inhabited areas	• carefully assess stability prior to allowing emergency/rescue workers into landslide area
residential structures	• damage to residential structures	• inhabited structures within landslide track	• cost for repair increases with extent of damage
water quality (community watersheds)	• turbidity from suspended sediment • damage/maintenance of intake structures	• suspended sediment in water • high proportion of suspended sediment deposited in watercourse • sediment or woody debris clogging intake	• water distribution network can switch to other sources may lead to reduced effects • prevent future sediment from reaching watercourse
Economic Resources			
utility corridors	• downtime utility cost • high repair costs • environmental damage (such as oil pipeline)	• utility corridor within landslide track • landslide impact destroys utility connections	• utility may remain operational, maintenance / preventative protection works needed (such as armouring over a pipeline) • utility traffic can be rerouted
transportation corridors	• loss of use • possible high repair costs	• transportation corridor within landslide track • landslide disrupts traffic flow	• repair cost depends on extent of damage • traffic can be rerouted
timber resources	• loss of merchantable timber	• merchantable trees within landslide track	• extent of loss depends on value of trees, time to planned harvest
Environmental Resources			
fisheries habitat	• infilling of spawning beds • destruction of off-channel habitat • loss of fish access	• overloading streams with sediment and woody debris • deposition of fine sediment in stream • landslide blocks stream / alters stream course	• sedimentation is insignificant compared to natural processes • sedimentation occurs at a time when no fish are present • potential for rehabilitation / mitigation (reconstruct habitat, prevent further sedimentation)
wildlife habitat	• loss of terrestrial wildlife habitat • depends on species present	• loss of wildlife trees or habitat in landslide track	• landslide may improve migration corridors • grass seeding landslide may improve forage for some animals
site productivity	• permanent / temporary loss of productive site • loss of agricultural land	• degree of loss depends on size of landslide (relative to crown closure) • extent of soil loss along landslide track	• potential for rehabilitation or natural regeneration • deposition area may be more productive than original site

mountainous terrain. A systematic approach to landslide investigation is critical to increasing the recognition of, and improving forest practices on, landslide-prone terrain.

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REFERENCES CITED

B.C. Ministry of Forests. Engineering Manual. Chapter 8: Risk Assessment, Page 20.

B.C. Resources Inventory Committee. 1996. Terrain Stability Mapping in British Columbia. Resources Inventory Committee Publications, Ministry of Forests and Ministry of Environment, Lands, and Parks.

B.C. Workers Compensation Board. 1998. Landslide Assessment requirements within Proposed Forestry Work Areas, Draft Regulations.

B.C. Ministry of Forests, 1997. Landslide Safety Assessments for Logging Operations. Memo to B.C. Coastal Forest Companies, October 27, 1997. (File 195-20/Research Circular 17275-01. Vancouver Forest Region.

Church, M. and Miles, M.J. 1987. Meterological antecedents to debris flow in southwest British Columbia: some case studies. *Appearing in* Reviews in Engineering Geology, Volume VII, Geological Society of America, Pages 63 - 79.

Hungr, O. 1995. A model for the runout analysis of flow slides, debris flows, and avalanches. Canadian Geotechnical Journal, 32: 115-126.

Morgan, G.C., Rawlings, G.E and Sobkowicz, J.C. 1992. Evaluating total Risk to Communities from Lange Debris Flows, in proceedings of Geotechnique and Natural Hazards, Vancouver Geotechnical Society and Canadian Geotechnical Society, BiTech Publishers, pp225-236.

VanDine, D.F. 1997. Landslide Hazard and Risk Assessments for Small Projects, Preliminary Studies and Emergency Response. *Appearing in* IUGS Working Group on Landslides, Committee on Risk Assessment, Cruden, D.M. and Fell, R. editors. Published by Balkema. Pages 365-369

Wise, M.P. 1997. Probabilistic Modelling of Debris Flow Travel Distance using Empirical Volumetric Relationships. M.A.Sc. Thesis, University of British Columbia.

Wise, M.P. and VanDine, D.F. 1998. Landslide Risk Assessment Associated with Forest Roads (Draft 1), unpublished report prepared for the Ministry of Forests / Council of Forest Industries Risk Management Subcommittee, 26 pages.

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