Terrain Stability Field Assessments in "Gentle over Steep" Terrain of the Southern Interior of British Columbia

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INTRODUCTION

This paper discusses the terrain, hydrologic and forest development factors that should be investigated as part of any Terrain Stability Field Assessment where there is the potential for the particular class of slope failures associated with forest industry practices known as "gentle-over-steep" (GoS) landslides. In the Southern Interior of British Columbia in the last several years there has been an increasing awareness that the majority of significant landslides related to forest industry practices in this region have been GoS type landslides. GoS landslides in the Shuswap and Okanagan Highlands have been responsible for the evacuation of residents, property damage and litigation (Anderson, et. al., 1997; Dobson Engineering Ltd. 1997), and loss of life (Schwab et. al., 1990).

Until recently there has been little discussion of the occurrence, processes and management implications of this class of landslides in the forestry geotechnical literature, or explicit recognition in forest practices regulations in British Columbia of the need to manage the risks associated with these slides.

GoS landslides are described as occurring "some distance below roads, below a culvert or a point of accidental drainage discharge [where] the road itself is on gently-sloping, low-hazard terrain, and the landslide occurs on steeper terrain below." (Jordan, 2001). Landslides generally occur near a slope gradient break between the flatter lying terrain on which the road is constructed, and steeper gradient terrain downslope. This may occur from several to several hundred metres downslope of the road, and the physical connection between the forestry development and off site landslide consists entirely of water movement between the two.

The Southern Interior of British Columbia is defined in this paper as the area covered by the Kamloops and Nelson Forest Regions. This paper builds on earlier work in the Nelson Forest Region (Jordan, 2001), which provided both landslide inventory data for the Slocan Valley in the southern Columbia Mountains, and discussed GoS landslide characteristics and processes. The Slocan study inventoried approximately 190 strictly drainage related failures, many of which were GoS landslides. Most of the my conclusions are drawn from observations of about 100 GoS landslides in the Shuswap Highlands and, to a lesser degree, on the Kamloops Plateau, both in the Kamloops Forest Region.

This paper first discusses GoS landslide characteristics and processes, to provide the background for understanding the suggested hazard assessment procedures. GoS landslide risks in the Southern Interior are briefly discussed. The suggested procedure for conducting an assessment of GoS landslide hazard is broken down into five terrain and development factors, and each discussed with examples. Finally a framework for managing GoS landslide hazards is briefly presented.

GoS LANDSLIDE CHARACTERISTICS AND PROCESSES

Forest roads, and to a lesser extent trails, situated on gentle (6 to 26%) to moderately sloping (27 to 50%) terrain can intercept surface and subsurface hillslope drainage. Drainage accumulates or is concentrated down the ditch or road surface, and redirected to a single exit point from the road. This is usually a culvert, cross ditch or switchback, but can be a random point of discharge caused by road prism failure. This discharge then travels as either surface or subsurface flow, some distance across gentle to moderate gradient terrain downslope of the road. When it reaches a slope break to moderately steep (50 to 70%) to steep (>70%) gradient slopes, a landslide can occur.

Although deep-seated landslides have been observed downslope of the outlet of concentrated road drainage, most GoS landslides occur in shallow, relatively permeable weathered till or colluvium overlying relatively impermeable till or bedrock.

Because they are much longer than deep, these landslides can be modelled by an infinite slope analysis, with the soil shear strength, $S_{s,}$, or the resistance to sliding, expressed as:

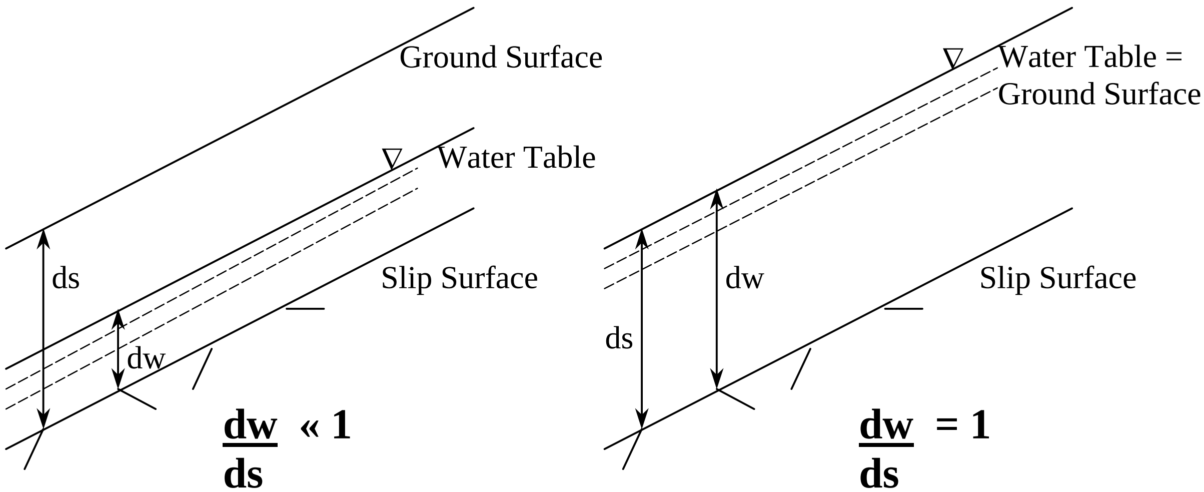
Equation 1. $$S_s = c' + (\sigma - u) \tan\phi'$$

where c' is apparent cohesion, σ is the total normal stress due to the weight of soil and water, u is pore pressure due to the depth of the saturated zone, and ϕ' is the effective angle of internal friction of the soil. A slope failure will occur when the shear stress, or the forces promoting sliding (the weight of soil and water on the slope) exceeds the shear strength.

The thin weathered till and colluvial soils on steep slopes in south western B.C. frequently have a very low clay content and are often considered cohesionless. It is assumed that on marginally stable slopes, the effect of differing internal friction angles of the commonly encountered morainal and colluvial soils of the Southern Interior, is minor compared to the effect of changes in pore pressures. Because the landslide-prone terrain is some distance downslope of the road prism, and is as likely to occur in forested as in harvested terrain (Jordan, 2001), these landslides are presumably caused by the artificially increased water volume from the road. This extra water increases pore water pressure (u) and decreases the effective stress (σ - u), in soils on the steeper gradient slopes some distance downslope of the road.

It has been shown that for cohesionless soils, as the ratio of the height of the saturated zone (dw) to the total soil column depth (ds) increases, the effective stress decreases (Skempton and Delory, 1957). In this paper the ratio dw/ds is used as an expression of the effect of the saturated zone on slope stability. Note that because effective stress, and thus shear stress, is proportional to the ratio dw/ds, and not simply the saturated zone height (dw), shallow cohesionless soils are less stable than deep soils, given the same saturated zone depth.

Figure 1: Long Term Maximum Water Table Levels



a. Southern Interior **b. Coast**

Figure 1 shows long term maximum water table levels for steeper slopes on the Coast and in the Southern Interior of B.C, as implied by inventories of forest development related landslides (Table 1).

Table 1: Comparative Landslide Statistics

Region	**Landslide Cause (%)**				
	Clearcut (root strength)	**Drainage (off-site)**	Road Fill	Cutslope/ Others	**dw/ds**
Coast – Clayoquot Sound West Coast Vancouver Isl. (Jakob, 2000)	**54**	**0**	31	15	**=1**
Southern Interior – Slocan Valley, Columbia Mountains (Jordan, 2001)	**3**	**43**	47	7	**«1**

Roughly half of all forestry related landslides in both the Coast and in the Columbia Mountain studies are caused by road prism failures. Of the remaining half, the distribution of landslide causes between the Coast and Southern Interior are the opposite of each other. On the Coast about half of all slides were judged to have occurred in clearcuts with no influence from road prisms or road drainage diversion, i.e. there were no strictly drainage related or GoS landslides. In the Columbia Mountains, almost half of all slides were off-site, drainage diversion failures, many of which were GoS landslides, and clearcut failures were rare. In the Shuswap Highlands, which are characterized by large areas of gently sloping upland plateau incised by lake and river valleys (Figure 2), there is a wider distribution of a gentle-over-steep terrain configuration than in more mountainous areas of the Southern Interior. GoS landslides are therefore likely to make up a larger proportion of forestry related landslides in the Shuswap Highlands than in the Columbia Mountains. The Cariboo Highlands to the north and the Okanagan Highlands to the south are similar in physiography to the Shuswaps and likely in landslide occurrence as well.

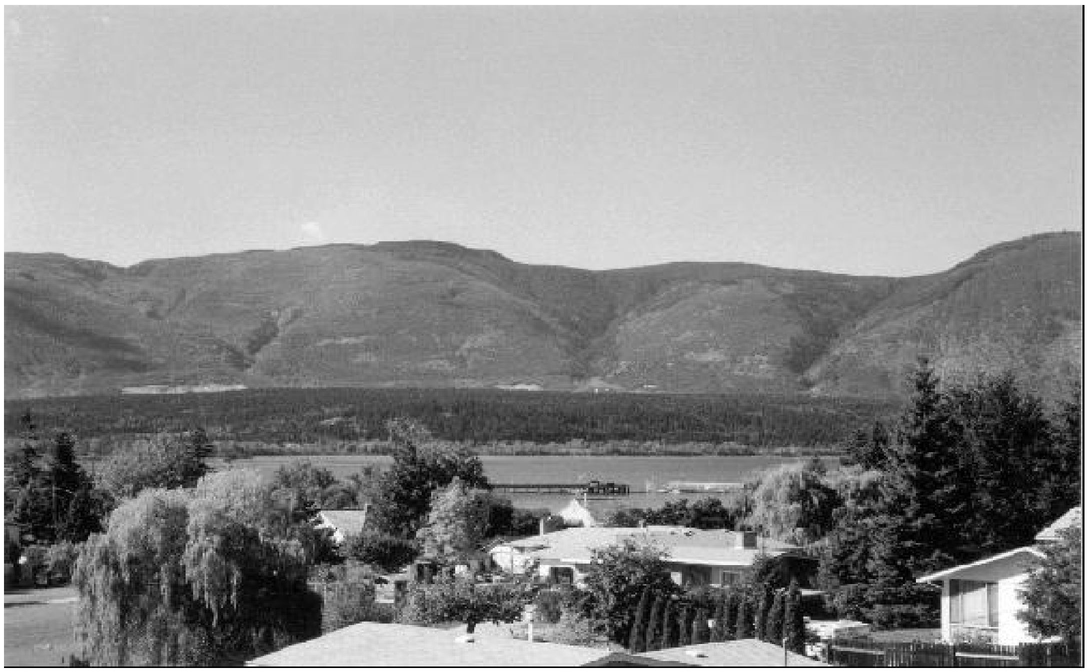


Figure 2. Typical Shuswap Highlands landform at Fly Hills, overlooking the town of Salmon Arm, B.C. Gently sloping upland with steeper stream incision into valley walls.

While there may be differences between the Coast and Southern Interior in terms of slope physiography and soil texture, no parameter is as clearly divergent as the precipitation inputs to each area. Total annual precipitation at valley bottom on the west coast of Vancouver Island is over 3000mm per year (Atmospheric Environment Service, 1993). At valley bottom in the south Columbia Mountains it is around 700mm per year, and in the Shuswap Highlands it is about 500mm per year. Total annual precipitation on the Coast is therefore approximately 4 to 6 times greater than in the Southern Interior. Maximum rainfall amounts in individual rainstorm events are also greater by a similar proportion.

The difference in landslide causes between the Coast and south Columbia Mountains inventories can be explained if we assume that this large difference in precipitation results in different maximum long-term values for the relative depth of the saturated zone in shallow soils, as shown in Figures 1a and 1b.

On the Coast, if the water table has periodically been at the highest level possible, at the ground surface, the soil column is totally saturated and further water input runs off as surface flow (Figure 1b). Assuming the soil internal friction angle (ϕ) is relatively unchanging over the time periods of hundreds to thousands of years we are discussing here, for cohesionless soils with the effective stress periodically at the minimal possible value, on some marginally stable slopes it must be tree root strength that is preventing sliding. For many locations on the Coast of B.C. the shear strength equation can be expressed as:

Equation 2. $$S_s = r' + (\sigma - u) \tan\phi'$$

where r' is root strength. We know this because the coastal inventory results tell us that when we cut trees down and tree roots die and lose their strength, landslides occur.

In the south Columbia Mountains the inventory shows that there are almost no landslides due to harvesting alone. The much lower precipitation here is generally not enough to effect a high degree of saturation of the soil column on moderately steep to steep slopes, i.e. dw/ds is always « 1, and effective stress remains high (Figure 1a). Therefore relative to the effective stress, root strength is a minor contributor to slope stability. In the drier areas of the Southern Interior of B.C this effect is probably equally or more pronounced.

Commonly in the Southern Interior then, we can have a situation on an otherwise marginally stable slope where, over the long term, there is a large unsaturated portion of the soil column above the saturated zone. If by our forest practices we deliver a volume of water to that slope that is much greater than natural maximums, we can cause unprecedented saturation of this upper soil column and trigger a slide. And the landslide inventory results show this – in the Southern Interior, when drainage is concentrated by forest roads and redirected onto steeper downslope areas, there are GoS landslides.

A further important effect of road drainage diversion is that the increased flows can be maintained on the marginally stable slope for some period of time before a landslide occurs. Soil pore pressures can increase and soil shear strength decrease for a long distance downslope. Because the factor of safety is thus lowered over a long downslope distance, when critical factor of safety values are reached at the head of the slope, the whole slope fails and a very large landslide occurs (Jordan, 2001). For this reason GoS landslides are commonly larger than road prism failures, and most large landslides with significant downslope impacts in the Southern Interior are GoS slides.

GoS LANDSLIDE RISKS

In much of the Southern Interior, and particularly in the Shuswap Highlands where uplands are not steep, most steeper slopes are located on river and lake valley walls, and are often are directly connected by steep slopes to these water courses. There is also increasingly widespread human settlement of these lower valley walls, and on valley bottom fans and floodplains. Thus, landslides on these valley walls frequently impact water courses that are drinking water sources, as well as human habitation and private property that are often located in landslide runout zones. While there are about 1/10 the number of landslides per unit area in the Southern Interior as on the outer Coast (Jordan, 2001), of all forestry related landslide in B.C., GoS landslides in the Southern Interior form a significant portion of those responsible for private property damage, litigation against the forest industry, threats to human safety, and loss of life.

TSFA PROCEDURES IN GoS LANDSLIDE PRONE TERRAIN

There are existing guidelines on how to carry out a TSFA and what is considered good professional practice (Horel, et. al, 1996, FPC, 1999 and Turner, et. al., 2001). This discussion is restricted to five specific factors that need to be addressed where there may be a GoS landslide potential. They are:

1. The downslope factor of safety – how much additional water could a steeper slope, located some distance downslope of the road, receive before failing?
2. Site moisture regime – how much surface and subsurface hillslope water runoff could be available to be intercepted?
3. Prism conditions – how could the road prism intercept hillslope runoff?
4. Grade configuration – how could the road alignment concentrate and redirect water?
5. Slope drainage connectivity – how will water move between its exit point from the prism and potentially unstable downslope terrain?

Note that points 1, 2 and 5 address site terrain and hydrologic conditions and points 3 and 4 address road design and construction factors.

There is no set sequence to follow in assessing these factors, but rather an iterative approach needs to be taken. The more hazardous any particular factor or set of factors appears to be, the more detailed the investigation of the others should be. It will become apparent that most of the assessment time should be spent both up and down slope from the road location.

The downslope factor of safety

To understand how proposed forestry development may impact downslope stability, it is necessary to have some knowledge of prior slope stability conditions. For GoS landslides the question is basically how much additional water can the slope receive before a landslide occurs? In geotechnical terms, the factor of safety is the ratio of the resistance to sliding (shear strength, Equation 2) to the forces promoting sliding (shear stress) at the point of potential failure. When the factor of safety drops below 1, failure can occur.

In the forestry context, the assessment of existing slope stability is rarely a quantitative factor of safety analysis using subsurface geotechnical data. Rather the method is qualitative and comparative. A comparative method requires investigation of existing local landslides, geomorphic and hydrological processes, and the hillslope response to previous forestry developments in similar terrain in surrounding areas. The investigation of adjacent areas must be thorough enough so that the basis of comparison can be clearly understood. As with all professional geotechnical reports, “Sufficient information and explanation should be provided to allow another qualified professional to follow the author’s logic . . . (Horel, et. al., 1996).

Where GoS landslides have occurred in the Shuswap Highlands, as often as not, in the immediate area there is no recent or relic landslide activity visible on pre-failure air photos. This means that the lack of slope instability indicators may <u>not</u> be an indication of how sensitive the site could be to drainage diversion, and an understanding of processes in surrounding areas is necessary.

Utilizing air photos and terrain mapping, as well as topographic and bedrock geological mapping prior to field work, will greatly increase the efficient use of field time. If there are existing landslides in adjacent areas, historic air photo series are probably the only way of determining their chronological relationship to forestry developments. Determining the actual cause of existing landslides is critical to making a comparative assessment of areas with similar terrain and proposed development. In areas with a low landslide frequency it may be necessary to inspect terrain mapping and multiple air photos in a wide area around the assessment site, to determine if there is similar terrain that has or hasn't been impacted by previous forest development. All relevant landslides should be investigated on the ground to develop terrain stability criteria, and this can require as much time as is spent assessing the proposed development and downslope areas.

Jordan found that in the southern Columbia Mountains, GoS landslides typically occur where gentle slopes break to gradients of 50 to 70%, on terrain classified in terrains stability hazard mapping as Class III, or stable (Jordan, 2001). In the Shuswap Highlands GoS landslides generally occur on terrain mapped as TSHC IV, or potentially unstable[1], and the terrain mapping is a very useful tool, both in identifying the potential hazard and the terrain characteristics.

Gullies are frequently a factor in GoS slides. Landslides may initiate as gully sidewall failures, or as open slope debris slides that enter a gully some distance downslope and become channelized debris flows. The presence of gullies, even those starting hundreds of metres downslope of the road or slope break to steeper terrain, can greatly increase both the likelihood of landslide initiation and the potential landslide run out distance.

In assessing existing GoS landslides, one of the main criteria for judging the pre-failure slope sensitivity is the amount of water diverted onto the slope to cause the failure. For example, sites have been observed with relatively minor cutslope seepage interception, and culvert spacing as low as 50 m, where significant landslides have occurred downslope of almost every culvert. Obviously this area and areas with similar terrain are only marginally stable, and depending on the risk, development must proceed very cautiously, or not at all.

Conversely, it has been observed that significant landslides have been caused by the cumulative concentration of up to 20 ha of hillslope drainage to a single culvert (Figure 3), or the total diversion of a stream onto the failed slope (Figures 4 and 5). In these cases, it was concluded that the factor of safety of these slopes was not particularly low, and harvesting with adequate forest road and trail drainage management would not result in a significant landslide hazard.

Determining the flow paths and size of water diversions responsible for landslides may require traversing many hundreds of metres upslope of the slide to the road or trail drainage source, and then tracing the drainage concentration and interception that occurred along and above that source, as shown in Figure 3.

1. In the Salmon Arm Forest District much of terrain stability hazard mapping identifies terrain with normal morainal and colluvial soils, and slope gradients > 60%, as Class IV or IVR, or potentially unstable. (EBA Engineering Consultants Ltd., 1997 – 2000).

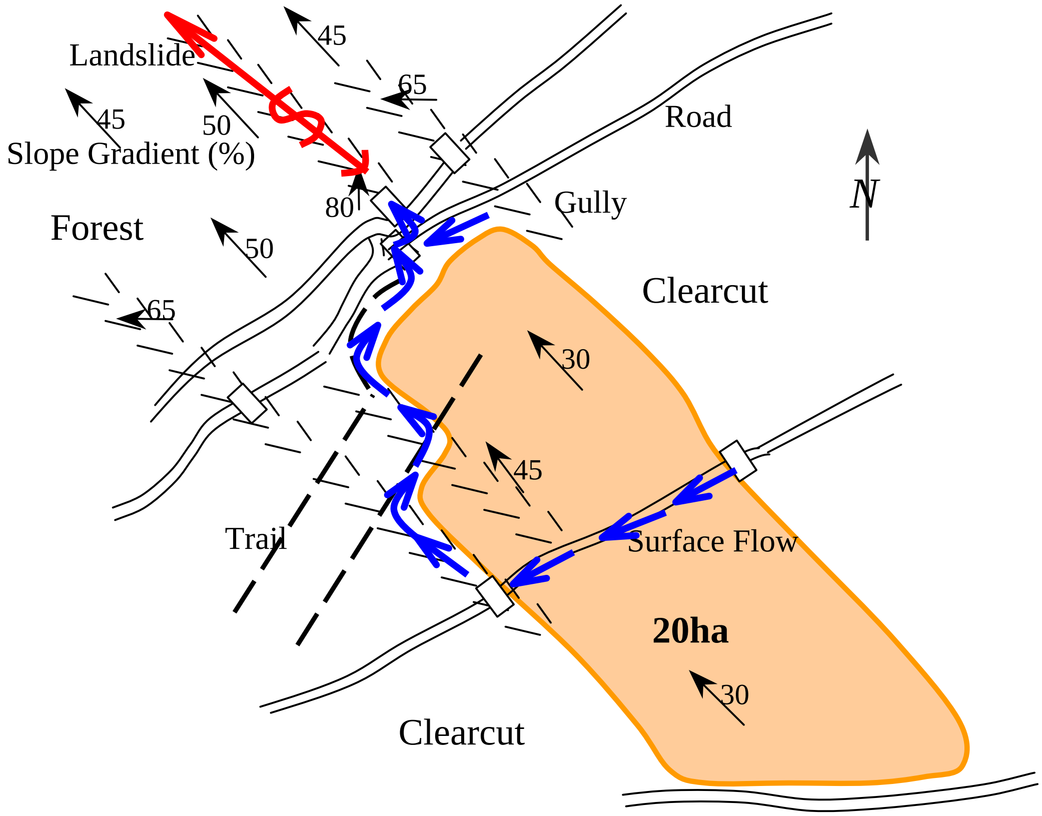


Figure 3. Hillslope drainage concentration from 20 ha area.

Once the downslope sensitivity to introduced drainage has been established for the terrain type in question, there can be a qualitative statement of the likelihood of a downslope landslide and its potential magnitude, given some quantity of introduced water required to initiate that slide. With an understanding of the other site and development factors, the necessary recommendations can be made to prevent that amount of water from being directed onto the slope.

Site moisture regime

The site moisture regime is the form and magnitude of hillslope runoff that a proposed road or trail will encounter. While it may seem obvious that a wetter site will have a higher hazard than a drier site, this may in fact not always be so. Previously in this paper it was shown that the empirical evidence suggests drier regions may be more susceptible to GoS landslides than wetter ones. However, at a locally wetter site in a drier region, there may be more moisture available to be intercepted by a road or trail, and thus a higher hazard.

GoS slides have been associated with varying climatic inputs, from large, relatively infrequent rain and/or snowmelt events to relatively normal spring snowmelt rates. The climatic input required to initiate a landslide can be less critical than the magnitude of runoff interception and concentration.

Particularly on gently sloping terrain, road drainage structures have traditionally been designed to prevent road prism failures such as culvert wash-outs. However, ditches and culverts that can safely pass a 50 or 100 year runoff event may easily divert enough hillslope runoff during much smaller events to cause a GoS landslide. Generally, if the downslope area has been determined to be potentially unstable, and the proposed road prism and grade has the potential to intercept and concentrate flow, a GoS landslide is possible.

During a site assessment it is important to note the types and location of potential slope drainage elements. These can be permanent or seasonal streams, seepage sites, dry swales or gullies, and on uniform open slopes, the depth to an impermeable layer.

Upslope drainage can be in a natural, undisturbed state, or there can be abundant upslope skid trails and roads that have intercepted, concentrated and redirected drainage, often for considerable distances (Figure 3). In assessing the moisture regime at the road alignment, the connections to any existing upslope developments should be determined. Particularly during road upgrading and deactivation, which occur in developed areas, alterations to upslope drainage patterns should be investigated. A drainage plan is often required, both of natural and development related upslope drainage paths. A drainage plan methodology is discussed elsewhere in this volume (Green, 2002) and is an important tool in managing GoS landslide hazards.

Preparing a drainage plan can require traversing many hundreds of metres upslope of the site being investigated, and can take as much time as assessing the downslope safety factor. It may also show that it is better to correct redirected upslope drainage, rather than attempt to manage artificially high flows at the road alignment being assessed.

An understanding of the volume, type and location of upslope flow paths is used to determine how the hillslope drainage could interact with the prism and alignment of proposed or existing roads.

Road prism conditions

The different types of hillslope drainage create different drainage interception problems at the road prism. Stream crossings have the potential to divert the largest flow volumes, and undersized or poorly installed cross drains have caused numerous GoS landslides. Figure 4 shows a stream and culvert under normal spring freshet conditions on an active forest road. It is apparent that under extreme runoff conditions the capacity of this culvert would likely be exceeded. It may be that it was believed the road prism wasn't at risk, because excess flow could escape down the ditch at the top of the picture, and this is precisely what occurred. Peak stream flows overtopped and eroded the ditch block, travelled 300m down a 10 to 15% ditch grade, washed out another culvert, and exited the road. All flow infiltrated into a 100m wide flat bench a short distance downslope of the road. The landslide shown in Figure 5 initiated just below the bench on an 80% slope, 100m directly downslope of the where redirected flow left the road.

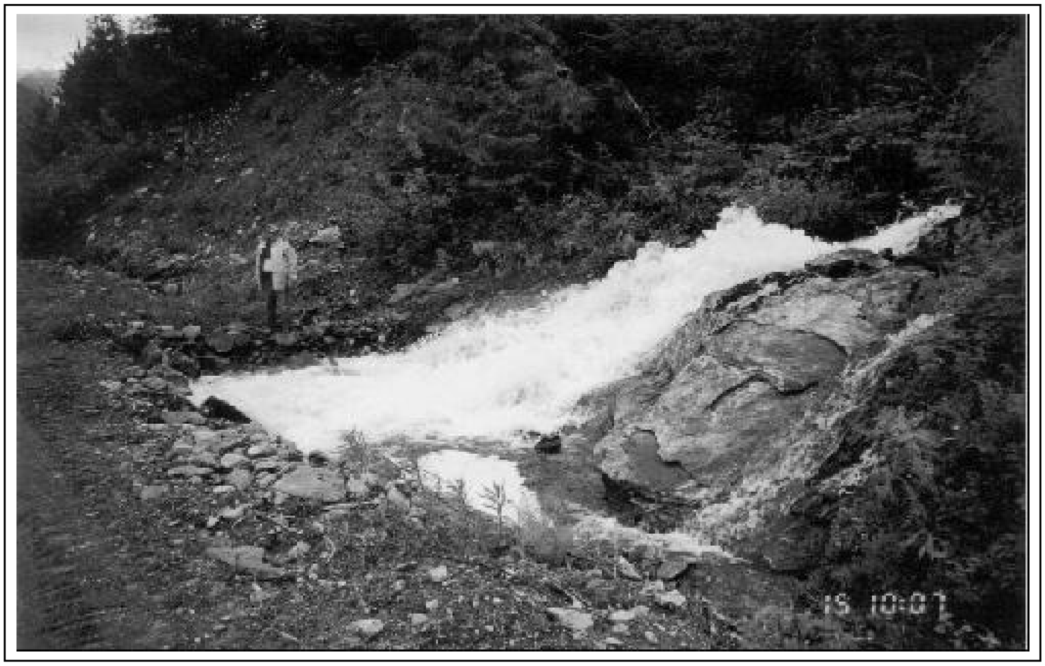


Figure 4. **Large seasonal stream flow, relative to 600 mm culvert. Peak flows escaped down the ditch towards top of photo, causing the landslide shown in Figure 5.**

Figure 5. Gentle-over-steep landslide caused by undersized culvert and stream diversion.

In GoS landslide prone terrain, designing drainage to protect the road prism while allowing excess flows to be diverted out of natural drainage paths can increase the landslide hazard. Road drainage structures should be designed to both protect the prism and prevent drainage diversion.

In relatively minor swales or gullies, failure to recognize the potential for seasonal flows can cause similar problems. Often there is little or no evidence along the road alignment of the existence of upslope drainage diversions that could deliver abnormally large flows to the road in an otherwise dry swale, with the result that road drainage structures including culverts, cross ditches and ditch blocks, have been under-designed.

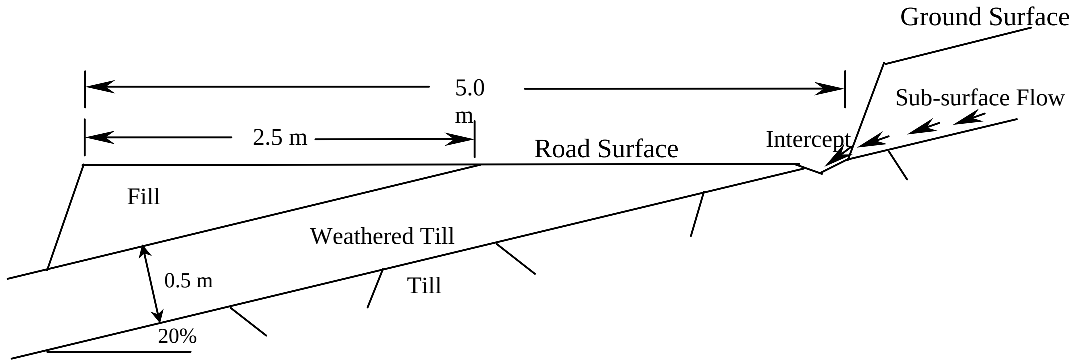
On uniform slopes it may be necessary to understand the near surface soil layering to be able to predict what effect a proposed road cut will have on interception of subsurface drainage. GoS landslides have been initiated by nothing more than normal ditch lengths intercepting seasonal subsurface groundwater flow from cutslopes that appear dry for most of the year.

For example, a common soil structure in the Southern Interior is a 0.5 m thick, loose, relatively permeable weathered till overlying dense till. Generally, natural subsurface drainage on well drained forested hillslopes in the Southern Interior can be expected to be confined to relatively narrow band at the base of the permeable layer, due to the rapid infiltration and soil drainage effected by macropores (root casts and animal burrows, etc.). A thin perched water table forms at the base of the permeable upper weathered till layer (Figure 6).

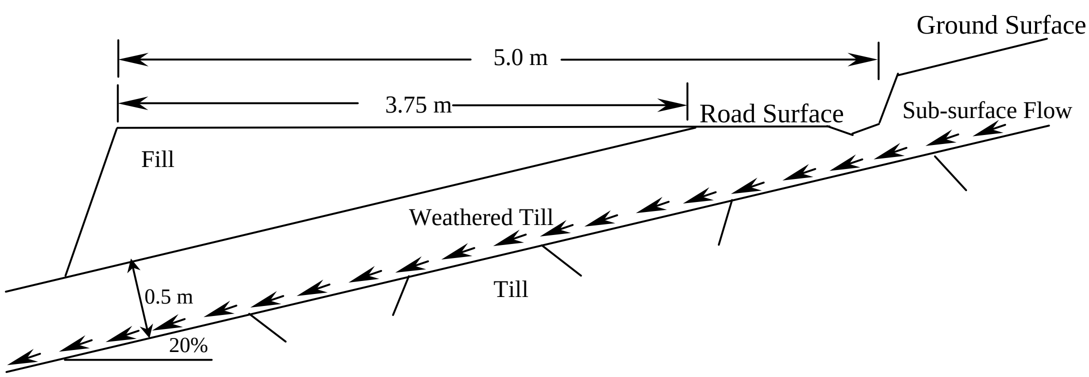
Simple trigonometry can be used to calculate the expected impact of the proposed road prism on subsurface drainage, as shown in Figure 6a. Minimizing the road width is the simplest way to reduce the road prism incision into the hillslope, and avoid intercepting subsurface flow. Where this is not feasible, widening the fill portion of the road prism can achieve the same effect. Under the conditions shown in Figure 6, increasing the fill width by 1.25 m will increase the depth to the impervious layer by 0.35 m, making it unlikely that the cut slope will intercept significant subsurface flow (Figure 6b). On steeper slopes this technique will work if there is a thicker permeable soil layer.

In the example shown, the fill volume will approximately double, and will require importing fill material. Depending on the overall cut and fill mass balance along the road alignment, increasing the fill width to reduce the cutslope height may be cost effective in preventing intercepting subsurface drainage, and reducing the GoS landslide hazard.

Figure 6: Road prism geometry and subsurface drainage interception.



a. Balanced bench construction on a 20% gradient slope with a 5.0 m wide road prism and a 0.5 m depth to impervious layer.



b. On the same slope, with road fill width increased by 1.25m.

Road Grade Configuration

The road grade is defined as the road surface or ditch slope gradient along the road alignment profile. Long continuous road grades can always create the potential for drainage concentration and redirection. However, if there is no road grade to redirect intercepted flow, there will be no increase in landslide hazard due to drainage diversion.

A rolling grade, with the road grade upslope in both directions away from cross drains, limits the length of road along which drainage can be concentrated. Even if culverts in the grade dip should fail, stream flow could not escape along the alignment, but would be retained in its natural drainage path.

If the road location is preliminary at the time of the assessment, and has not been traversed, grades will have to be measured through critical areas. If the alignment has been traversed, the assessor should obtain the traverse notes, or preferably the road plan and profiles. With good road grade information and terrain stability hazard mapping, potential problem areas can be identified in the office, allowing for more efficient use of field time. If there is no preliminary alignment at the time of the traverse, there may be an opportunity to use road grade design to reduce a potential GoS landslide hazard.

If there is a potential downslope hazard and a consistent road grade, the level of attention given to drainage design, installation, maintenance and deactivation should increase accordingly.

Slope drainage connectivity

An important and difficult question in assessing GoS landslide hazards is how far downslope from development should the slope stability investigation be concerned with? That is, how far downslope of a road or trail can a GoS landslide be initiated?

In the Columbia Mountains, GoS landslides initiating 600 to 800m downslope of the water source have been reported (BGC Engineering, 2001, and Jordan, 1999). In the Shuswap Highlands, the author has observed GoS landslide initiation commonly occurring at slope breaks located from a few metres up to approximately 200m downslope of the road on open slopes, and up to 300m in confined swales or gullies. With a large enough drainage diversion and sensitive enough downslope terrain, much greater distances are possible, and have been reported (VanBuskirk, 2002).

The runoff, infiltration and pore pressure interactions downslope of the road are probably the least well understood component of GoS landslide processes. Once the redirected water leaves the road, it is travelling over or through gentle to moderate gradient terrain. Depending on the volume of flow and the infiltration characteristics of the slope, redirected water may infiltrate a short distance downslope of the cross drain outlet, travel as overland flow some distance before infiltrating, or never totally infiltrate before joining some downslope water course. It has been noted that “because the hydraulic conductivity of surface soils varies so greatly, individual hillslopes often exhibit different runoff-generating mechanisms at different places during the same storm, or at the same place during different storms” and complexities of geologic structure, layered soils, and saturated-unsaturated interactions “can have significant impacts on infiltration rates and growth and decay of pore pressures through time” (Freeze, 1987).

So while there are many possible road drainage, slope runoff and infiltration process interactions, it is likely that in a particular region, most GoS landslides will be the result of a small set of those possibilities. Research into existing landslides is needed to determine what are the terrain and hydrological parameters influencing the downslope distance over which redirected water could have an effect[2]. Until we have a better understanding of the way introduced water behaves between the development and the landslide, most assessments will depend on the comparative assessment method discussed earlier in this paper.

The following discussion of subsurface process uses one possible model for this behaviour. It is intended to illustrate one of the downslope drainage issues to be considered when assessing the GoS landslide hazard.

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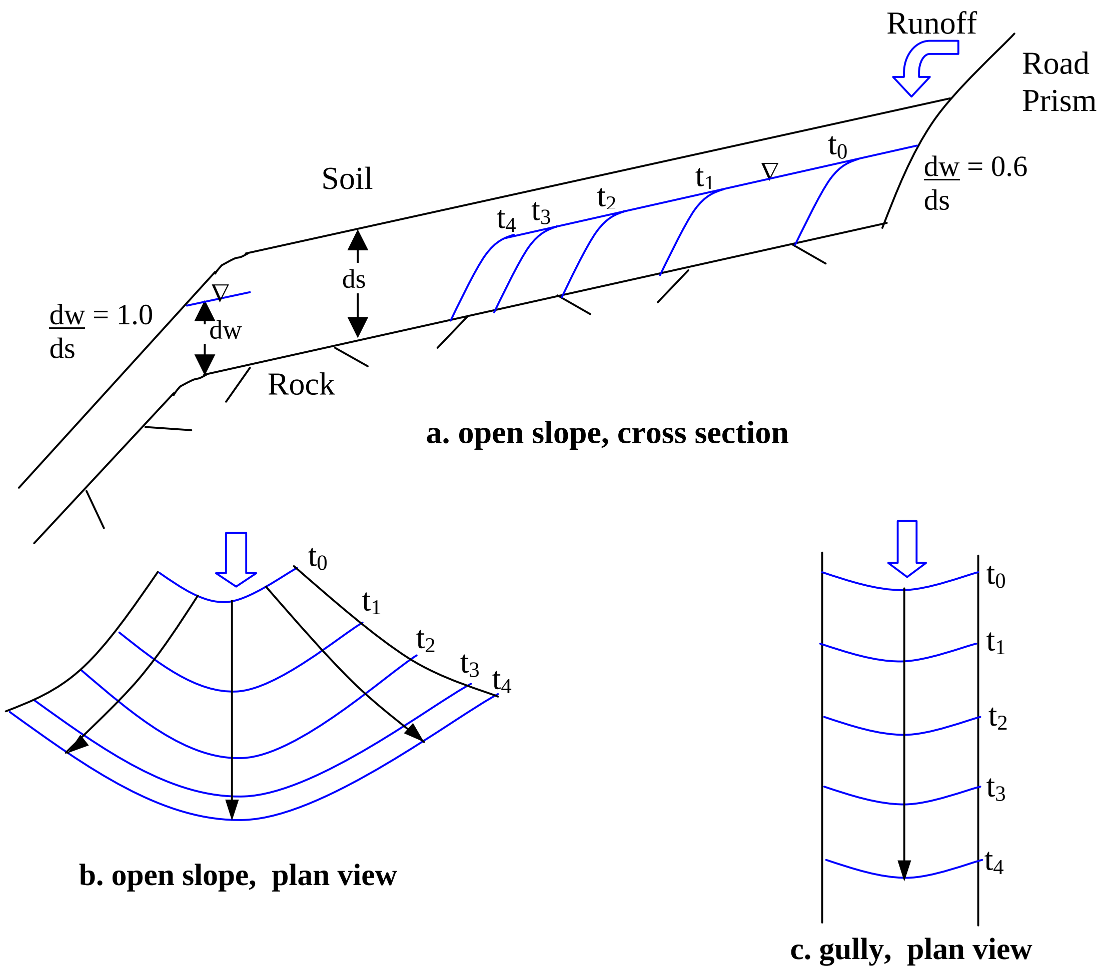
2. Research into this and other GoS landslide issues will be carried out in selected areas in the Southern Interior over the next few years (Stead, D., 2001)

In the Shuswap Highlands, many GoS landslides occur where the distance between the road and slope break is less than 100m. Fewer landslides occur when the distance is between 100 and 200 m, and fewer yet when the distance is between 200 and 300 m. Over 300 m, only isolated incidents are known. The fact that the number of landslides decrease with increasing distance between water source and slope break suggests that some dissipation of water occurs as the water moves between the gentle terrain between the road and steeper slopes. This may be from infiltration losses to deeper groundwater recharge, or from lateral dispersion as shown in Figure 7.

It is assumed that at the start of a runoff event (t_0) most of the water exiting a culvert infiltrates rapidly into the soil column a short distance downslope of the cross drain. This is a commonly observed above GoS landslides in the Shuswap Highlands. Some new value of dw/ds, which is higher than the slope has historically experienced, develops just downslope of the road. As time progresses this saturated front, or groundwater mound, extends downslope through successive equal time intervals ($t_1 - t_0 = t_2 - t_1$, etc.)

Figure 7: Subsurface drainage downslope of a cross drain during an extreme runoff event.



In relatively uniform soils, there will be a lateral hydraulic head gradient that will cause the saturated front to spread out on both sides of the main flow path (Figure 7b). Assuming a steady state water supply from the cross drain for the duration of a runoff event, as some water flows laterally there will be less available to supply the downslope movement of the elevated saturated front. The distance the front extends will decrease for successive equal time intervals, as shown in Figures 7a and 7b. In this way the water table mound disperses laterally. Depending on the magnitude and duration of the runoff event, and the distance between water source and slope break, the critical elevated water table level may or may not reach the slope break.

Note that if the elevated water table reaches the slope break, not only is the slope steeper, but the soil is likely to be thinner on the steeper slope (Jordan, 2001). In the thinner soils, the ratio dw/ds increases, shear strength is reduced, and the landslide hazard increases.

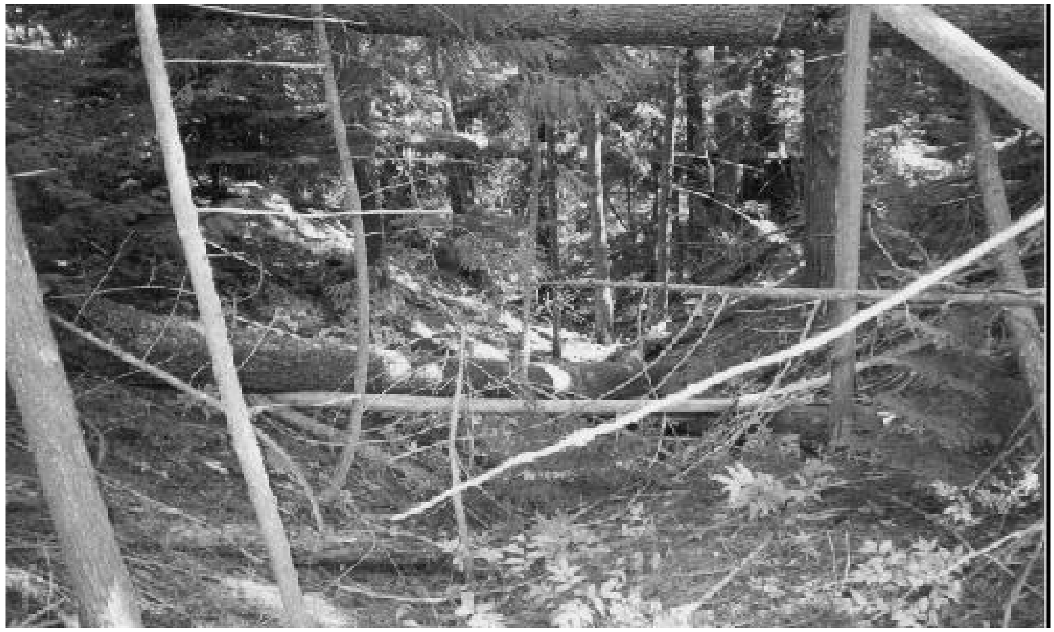
Figure 7c shows a plan view of the progress of the water table mound in a confined swale or gully, where the topography prevents lateral dispersion of subsurface flow. Without lateral dispersion the water table mound can travel further in a given time interval than on an open slope. With only subsurface flow in a gully downslope of a road, the elevated water table will be more likely to reach a distant slope break. So a gully may or may not be the preferred place to direct concentrated road drainage in this type of terrain.

Note that in this case we are talking about relic swales or gullies where the water table generally doesn't reaches the ground surface and saturated overland flow seldom or never occurs, unlike gullies that carry seasonal or permanent streams. In the drier Plateau and Highlands Regions relic "dry" swales or gullies are common (Figure 8). They may be less so in the wetter Columbia Mountains to the east. They probably formed during periods of extreme runoff volumes following deglaciation, or other wetter climatic intervals, thousands of years ago. These types of gullies can be identified by a uniform forest cover, a well developed 'A' soil horizon, and no evidence of sediment or litter movement by surface flows in the bottom of the feature.

Note that not only can a gully extend the downslope distance redirected drainage can travel, but since in relic gullies dw/ds has generally been «1.0, the gully sideslopes and base may themselves be sensitive to water table and pore pressure increases.

It is common practice to routinely culvert swales and gullies along a road alignment. Where this simply maintains a natural drainage path across the road prism it is usually good practice. Where the culvert is also the potential exit point of concentrated road drainage, the situation can be more complex. Where other factors indicate there is a potential drainage related landslide hazard, some understanding of the subsurface soil saturation and pore pressure history is warranted, and this can often be deduced from existing site conditions. This doesn't mean that swales and gullies may not be the preferred place to direct concentrated flows. To assess each situation, it will require knowledge of regional terrain and hydrologic characteristics, as well as the specific site conditions.

Figure 8: Typical relic "dry" gully in the Shuswap Highlands near Sicamous. B.C.



In any terrain, probably the worst place to direct road drainage is towards steep sideslopes of a gully containing a stream. GoS debris slides initiating on steep gully sideslopes can initiate debris flows by impacting the saturated channel, and have caused the largest and most destructive landslides in the Southern Interior of B.C.

MANAGEMENT STRATEGIES IN GoS TERRAIN

Strategies to reduce the GoS landslide hazard can be grouped under three general headings. The choice of a particular action, and the extent to which it is implemented, will depend on operational constraints, the downslope hazard, and downslope and downstream risks. In general, one can:

- Eliminate hillslope drainage interception and concentration
- Limit drainage interception, concentration and redirection
- Limit the time during which potential drainage disruption can occur

Eliminate hillslope drainage interception and concentration
All GoS landslide problems start when hillslope drainage in some form is intercepted and concentrated by a road or trail. When downslope terrain is only marginally stable, the management strategy may have to be one of no potential drainage interception or concentration. Sites where small drainage concentrations can initiate landslides are not common, but need to be recognized where they occur, particularly where downslope risks are high. In the extreme case, this could mean no development should occur in a location that could impact sensitive downslope terrain.

Otherwise it means the road alignment and prism are designed so there is little or no chance of intercepting, or concentrating drainage. Permanent and seasonal stream crossings should be designed conservatively, and this may entail a detailed upslope investigation of natural or altered drainage contributing areas (Green, 2002).

Interception of subsurface drainage may be avoided by narrowing the road width or widening the road fill, as discussed earlier (Figure 6), or by installing continuous subgrade drainage. In these cases ditches and culverts may not be desirable, and in certain situations it can be a reasonable strategy to not install them, both to preclude drainage concentration, and to minimize the road prism width and cutslope height. In all these cases road surface drainage will likely have to be managed by avoiding long continuous grades, or by installing waterbars. On fairly flat grades, road outsloping can manage both hillslope and road surface runoff. Outsloping or ripping the compacted road surface may be necessary before other road deactivation works occur.

Limit drainage interception, concentration and redirection

Where the downslope sensitivity is less, but still of concern, drainage structures and their placement can be designed to minimize the occurrence of significant interception, concentration and redirection.

Interception can be minimized by ensuring all upslope drainage sources are identified, and permanent and seasonal stream crossings designed conservatively. All potential seepages should have cross drains, and road widths and cutslope heights should be minimized. Field assessments should ideally be done during the spring runoff season, as many runoff features flow for only a few weeks each year, and may not be evident during the dry season. A follow up site visit may be required after construction to check for seepage locations and drainage diversions that were not apparent before construction.

Drainage concentration down the road grade can be minimized by reducing the distance between cross drain structures (culverts, cross ditches and waterbars). Minimum cross drain spacing should be specified to the extent required by downslope sensitivities, site moisture conditions and other factors, not solely on road gradient as is common practice. Cross drains should have back-ups (ditch blocks, and/or water bars) that are designed, installed and maintained to prevent flow escaping down grade in the event of cross drain failure – even at the expense of the road prism. Designing the alignment grades so that there is a grade dip will reduce the likelihood of cross drain flow escaping down the road grade.

Swale and gully characteristics and their connection to steeper downslope terrain should be examined carefully before cross drain locations are selected, as discussed earlier (Figure 7). Where it is operationally feasible, or where downslope conditions dictate, the road alignment can be moved to a location that increases the distance between the road and steeper, marginally stable slopes.

Limit the time during which potential drainage disruption can occur

GoS landslides in the Southern Interior commonly occur during spring snowmelt (Jordan, 2001). In the Shuswap Highlands they have occurred less often during relatively infrequent, moderate duration (days to weeks long) early summer precipitation, and rarely during early fall precipitation. Outside these times – particularly during the summer dry season – there is the opportunity to build roads and trails above high hazard or high risk slopes. If the road or trail is then deactivated and all natural drainage paths restored before the onset of the next wet season, the hazard or risk can be minimized.

Similarly for less unstable downslope areas, it may be reasonable to install roads with drainage structures that will disrupt natural hillslope drainage to some extent, if the time period they will be in place is short relative to the frequency of an extreme precipitation event judged to be large enough to trigger a slide. For example, site and development conditions at a particular site may indicate that a rare (50 to 100 year) climatic event would be required to cause a GoS landslide. If a road is planned for only 2 or 3 years between construction and deactivation, the probability of such an event occurring during the period of active use is low. Depending on the downslope risk, it may be reasonable to construct, use and deactivate a road within that short period.

It will require a degree of familiarity with local landslide occurrences and antecedent climatic conditions, existing slope sensitivities, and downslope risks in an area, to conduct this type of risk analysis. However, it has been the author's experience that with more detailed hazard and risk analysis, not only are potential liabilities better managed, but savings in reduced construction, maintenance and lost opportunity costs far outweigh assessment costs.

CONCLUSION

GoS landslides are caused by interactions between terrain, hydrological and development factors. An assessment of potential GoS landslide hazards requires evaluating each, and integrating how they could interact with each other. The skills required include knowledge of landslide processes, geomorphology, surface and subsurface hillslope hydrology, and forest road design and construction.

Until there is adequate research and a better understanding of parameters controlling GoS landslide occurrence, hazard assessment will rely primarily on comparing the site under consideration to other sites with similar terrain and developments. It would be prudent for the assessor to either have extensive experience in a particular area, or as part of the assessment to conduct a thorough investigation of the relevant surrounding terrain.

GoS landslides are fundamentally about the movement of water – upslope, along, and downslope of the road or trail in question. Thus much of the investigation should focus on terrain and hydrologic conditions some distance both up and downslope of the development, as well as on how the proposed development will connect the two. The better the understanding of these processes, the more effective, and cost effective, management of these landslide hazards and risks will be.

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