Terrain Stability Field Assessments in “Gentle-over-Steep” Terrain of the Southern Interior of British Columbia

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ABSTRACT

In the southern Interior of British Columbia, most significant landslides associated with forestry operations are related to drainage diversions by forest roads and trails located on gentle to moderately sloping terrain, some distance upslope from steeper, more landslide-prone terrain. The underlying slope stability processes and the concepts of drainage interception, concentration, and redirection are discussed. Five areas of focus are suggested for doing terrain stability field assessments in this environment: (1) the sensitivity of downslope terrain: how much additional water can the slope handle before failing? (2) site moisture regime: how much slope water could be available to be intercepted? (3) site geotechnical conditions: how effectively will the road prism intercept water? (4) road grade configuration: how effectively will the road alignment concentrate and redirect water? and (5) drainage connectivity between the road prism and downslope terrain: how will redirected water behave between the road prism and potentially unstable downslope terrain? Some methods and tools for answering these questions, and some design suggestions to deal with sensitive areas are presented.

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 most 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.

Gentle-over-steep 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 metres 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 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 and the current regulatory environment in British Columbia at the time of this writing 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 is 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 (6–26%) to moderately sloping (27–50%) terrain can intercept surface and subsurface hillslope drainage. Drainage accumulates or is concentrated down the ditch or road surface, and is 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 (50–70%) 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:

$$S_s = c' + (\sigma - \mu) \tan \phi'$$  \hspace{1cm} (1)

where: $c'$ = apparent cohesion, $\sigma$ = the total normal stress due to the weight of soil and water, $\mu$ = pore pressure due to the depth of the saturated zone, and $\phi'$ = 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) exceed the shear strength.
The thin weathered till and colluvial soils on steep slopes in southwestern British Columbia 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 with 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 (\( \mu \)) and decreases the effective stress (\( \sigma - \mu \)) 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 shows long-term maximum water table levels for steeper slopes on the Coast and in the southern Interior of British Columbia, as implied by inventories of forest development related landslides (Table 1).

### Table 1  Comparative landslide statistics

<table>
<thead>
<tr>
<th>Region</th>
<th>Clearcut (root strength)</th>
<th>Drainage (off-site)</th>
<th>Cutslope Road fill</th>
<th>Others</th>
<th>( dw/ds )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coast Clayoquot Sound, West</td>
<td>54</td>
<td>0</td>
<td>31</td>
<td>15</td>
<td>=1</td>
</tr>
<tr>
<td>Coast Vancouver Island</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Jakob 2000)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Southern Interior Slocan Valley, Columbia Mountains (Jordan 2001)</td>
<td>3</td>
<td>43</td>
<td>47</td>
<td>7</td>
<td>&lt;=1</td>
</tr>
</tbody>
</table>

Note: the symbol <= is used to indicate "much less than."

**Figure 1**  Long-term maximum water table levels for a) Southern Interior, b) Coast.
Roughly half of all forestry-related landslides on 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; 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. Gentle-over-steep 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.

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 3000 mm/yr (Environment Canada 1993). At valley bottom in the south Columbia Mountains it is around 700 mm/yr, and in the Shuswap Highlands it is about 500 mm/yr. Total annual precipitation on the Coast is therefore approximately 4–6 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 (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 ($\phi$) is relatively unchanging over periods of hundreds to

**Figure 2** Typical Shuswap Highlands landform at Fly Hills, overlooking the town of Salmon Arm, B.C. Note the gently sloping upland with steeper stream incision into valley walls.
thousands of years that 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 B.C. Coast, the shear strength equation can be expressed as:

\[ S_\gamma = r' + (\sigma_\Gamma - \mu) \tan \phi' \]  

where: \( r' \) = 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, this effect is probably equally or more pronounced.

Commonly in the southern Interior, therefore, 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. 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 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 factors 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 failures, and most large landslides with significant downslope impacts in the southern Interior are GoS slides.

**GOS LANDSLIDE RISKS AND REGULATORY ENVIRONMENT**

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 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 watercourses that are drinking water sources, as well as on human habitation and private property that are often located in landslide runout zones. While there are about one-tenth the number of landslides per unit area in the southern Interior as on the outer Coast (Jordan 2001), of all forestry-related landslides in British Columbia, 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.
In British Columbia at this time, landslide hazards related to forest roads are managed under the Forest Road Regulations (FRR) of the Forest Practices Code (FPC), which requires that before road construction or modification or deactivation, a terrain stability field assessment (TSFA) must be carried out by a qualified registered professional if the area has been recognized as having a potential landslide hazard (FRR Section 4 (5); B.C. Ministry of Forests 2000).

The purpose of a TSFA is “to describe the terrain conditions within a proposed cutblock or along a proposed section of road [author’s emphasis], evaluate the likely effect of timber harvesting or road construction on terrain stability, and recommend site-specific actions to reduce the likelihood of post-harvesting or road-related landslides…” (B.C. Ministry of Forests 1999). The forest industry has generally interpreted that the need for professional involvement in hazard assessment and road design is triggered by the hazard along the road location, and not the hazard downslope of the road. In the Columbia Mountains, GoS landslides are the primary cause of landslides from newly constructed roads (Jordan 2001). This finding suggests that industry practices are not adequately managing for this type of landslide hazard.

There is provision under the FPC for a B.C. Ministry of Forests District Manager (DM) to direct that a TSFA be carried out in any area where the DM identifies it is required (FRR Section 4 (5) (e); B.C. Ministry of Forests 2000). In at least one forest district, the GoS landslide problem has been recognized, and the DM has issued a directive informing licensees that TSFAS must address areas downslope of proposed roads and cutblocks (D. Hudson, B.C. Min. For. Salmon Arm Forest District, pers. comm., 2001).

In my experience in the Shuswap Highlands, the majority of landslides associated with road modification (upgrades) and deactivation are also GoS landslides. Some of the most serious recent landslides in the southern Interior have occurred within a few years of road upgrading (Dobson Engineering Ltd. 1997) or road deactivation (Schab et al. 1990), and have involved property damage, litigation, and loss of life. Upgrades and deactivation can disrupt long-established drainage patterns that have come to some stable equilibrium with surrounding terrain. Even restoring drainage to what were apparently pre-construction natural drainage paths has caused significant GoS landslides. In potential GoS landslide terrain, an investigation of upslope drainage contributing area and downslope stability conditions is at least as important when planning modification or deactivation of existing roads, as it is when planning new road construction.

Whatever the future regulatory framework for forest practices in British Columbia, regulators and professional practitioners—foresters, geoscientists, and engineers—should ensure that industry practices recognize the potential, and manage, for landslides occurring off-site from developments. The costs to the forest industry of not addressing this issue could turn out to be much greater than that required to manage it properly.

On the positive side, while the off-site GoS landslide potential may require as much or more assessment than the strictly on-site landslide potential, the assessment phase is generally a small part of total development costs. Construction costs are much greater, and it is almost always less expensive to design or correct road drainage than to address road prism stability issues with costly techniques such as full bench and end haul construction, or heavy fill pullback. In the southern Interior, improved assessments of drainage-related off-site landslide hazards should achieve both better management of actual risks, and likely some reduction in total engineering costs.
**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; B.C. Ministry of Forests 1999; 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 instead 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 upslope and downslope 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 basic question is 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 hydrologic 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, there is no recent or relic landslide activity visible in the immediate area on pre-failure air photos. This means that the lack of slope instability indicators may not be an indication of how sensitive the site could be to drainage diversion, and an understanding of processes in surrounding areas is necessary.

Using air photos and terrain mapping, as well as topographic and bedrock geological mapping prior to fieldwork, 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 has not been impacted by previous forest development. All relevant landslides should be investigated on the ground to develop terrain stability criteria; 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 50–70%, on terrain classified in terrain stability hazard mapping as Class 111, or stable (Jordan 2001). In the Shuswap Highlands, GoS landslides generally occur on terrain mapped as terrain stability hazard Class IV, or potentially unstable.1 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 side wall 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 runout 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.

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

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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 IVB, or potentially unstable (EBA Engineering Consultants Ltd. 1997–2000).
understanding of the other site and development factors, the necessary recommenda-
tions 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 not always be so. Previously in this paper it was shown that the empirical evidence suggests that 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.

Gentle-over-steep 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 washouts. 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 have 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 include permanent or seasonal streams, seepage sites, dry swales or gullies, and the depth to an impermeable layer on uniform open slopes.

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 publication (Green and Halleran 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 that the road prism was not at risk, because excess flow could escape down the ditch at the top of the picture; this is precisely what occurred. Peak streamflows overtopped and eroded the ditch block, travelled 300 m down a 10–15% ditch grade, washed out another culvert, and exited the road. All flow infiltrated into a 100 m 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, 100 m directly downslope of where the redirected flow left the road.

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

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**Figure 4** Large seasonal stream flow, relative to a 600-mm culvert. Peak flows escaped down the ditch towards top of photo, causing the landslide shown in Figure 5.
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, 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 cutslope will intercept significant subsurface flow (Figure 6b). On steeper slopes, this technique will work if there is a thicker permeable soil layer.

In the Figure 6 example, 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.

**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, streamflow 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.

**Figure 6**  *Road prism geometry and subsurface drainage interception.*
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 600–800 m downslope of the water source have been reported (P. Jordan, B.C. Min. For., Nelson Forest Region, pers. comm., 1999; BGC Engineering 2001). In the Shuswap Highlands, the author has observed GoS landslide initiation commonly occurring at slope breaks located from a few metres up to approximately 200 m downslope of the road on open slopes, and up to 300 m 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 (C. VanBuskirk, Terratch Consulting Ltd., pers. comm., 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 watercourse. Freeze (1987) 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.”

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 hydrologic parameters influencing the downslope distance over which redirected water could have an effect. 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.

In the Shuswap Highlands, many GoS landslides occur where the distance between the road and slope break is less than 100 m. 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 decreases with increasing distance between water source and slope break suggests that some dissipation of water

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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 (D. Stead, Simon Fraser Univ., Dep. Earth Sciences, pers. comm., 2001).
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 (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 occurrence is commonly observed above GoS landslides in the Shuswap Highlands. Some new value of \(dw/ds\), which is higher than that which 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 \((t_i - t_0 = t_j - t_i, \text{ etc.})\).

In relatively uniform soils, a lateral hydraulic head gradient 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, less water will be available to supply the downslope movement of the elevated saturated front because some water flows laterally. The distance that the front extends will decrease for successive equal time intervals (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

![Figure 7](https://example.com/figure7.png)

**Figure 7** Subsurface drainage downslope of a cross-drain during an extreme runoff event.
subsurface flow. Without lateral dispersion, the water table mound can travel farther 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. Therefore, 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 does not reach 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 that redirected drainage can travel, but because 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 that there is a potential drainage-related landslide hazard, some understanding of the subsurface soil saturation and pore pressure history is warranted; this can often be deduced from existing site conditions. This does not mean that swales and gullies may not be the preferred place to direct concentrated flows. Assessing each situation will require knowledge of regional terrain and hydrologic characteristics, as well as the specific site conditions.

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 British Columbia.

**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, the three strategies are:

- to eliminate hillslope drainage interception and concentration;
- to limit drainage interception, concentration, and redirection; and
- to limit the time during which potential drainage disruption can occur.

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 that no development should occur in a location that could impact sensitive downslope terrain. Otherwise, it means that the road alignment and prism are designed so that there is little or no chance of intercepting or concentrating drainage. Permanent and seasonal stream crossings should be designed conservatively; this may entail a detailed upslope investigation of natural or altered drainage contributing areas (Green and Halleran 2002).

Interception of subsurface drainage may be avoided by narrowing the road width or widening the road fill (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 water bars. 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.

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 that all upslope drainage sources are identified, and permanent and seasonal stream crossings designed conservatively. All potential seepage 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 water bars). Minimum cross-drain spacing should be specified to the extent required by downslope sensitivities, site moisture conditions, and other factors, not solely by 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, (see 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.

Gentle-over-steep 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 more stable downslope areas, it may be reasonable to install roads with drainage structures that will disrupt natural hillslope drainage to some extent, if the 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 2–3 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 is my 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.

CONCLUSIONS

Gentle-over-steep landslides are caused by interactions between terrain, hydrologic, 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 to conduct a thorough investigation of the relevant surrounding terrain as part of the assessment.

Gentle-over-steep 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.

ACKNOWLEDGEMENTS

Nigel Skermer helped clarify the soil mechanics and reviewed the discussion on landslide risks and the current regulatory environment. Peter Jordan and Calvin VanBuskirk reviewed the entire paper and suggested significant improvements, many of which were adopted.

REFERENCES


