GROUNDWATER BLOW-OFF AND PIPING DEBRIS FLOW FAILURES

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Abstract

Groundwater blow-off failures occur on slopes as a result of high groundwater pressures and high groundwater storage in bedded sediments combined with restricted drainage that results from the development of surface soils and vegetation or sometimes freezing of the surface. Failure occurs when the pressures increase to the point where local effective stress is close to zero. The surface layer is blown-off over a local area and rapid drainage of the stored groundwater results in piping. As the failure retrogresses, a characteristic amphitheater shaped depression is formed. As the mixture of soil, vegetation and water runs downslope, a debris flow often occurs and a gully may be eroded. This failure mode is common throughout western Canada and in other areas where high precipitation and bedded sediments occur, but has often gone unrecognized. The failures often occur cyclically as a result of subsequent soil and vegetation development over the failure. Groundwater drainage is the key to reducing the potential for future events and has been successfully used to reduce the chances of failures affecting pipelines, roads and gravel mines.

Résumé

Les ruptures d'éruptions d'eaux souterraines sur des pentes se produisent en raison de pressions élevées d'eaux souterraines et d'emmagasinage élevé d'eaux souterraines entre les sédiments déposés en couches et est combinés avec le drainage restreint en raison du développement des sols et de la végétation ou parfois de la congélation extérieure de la surface. Une rupture ce produit quand les pressions d'eaux souterraines grimpent jusqu'au point où les contraintes effectives locaux en-dessous de la couche extérieure est de près de zéro. La couche extérieure du sol est enlevée par une éruption au-dessus d'un secteur local et résulte à un drainage rapide d'eaux souterraines emmagasinagé et produit un effet de siphon. Pendant que la rupture ce rétrograde vers moins de débris, une dépression qui a les charatéristiques d'un amphithéâtre ce forme. Pendant que le sol, la végétation et l'eau se mélange en aval, une coulée de débris se passe en général et une ravine peut-être érodée. Ce mode de rupture s'est avéré commun dans l'ouest du Canada et dans d'autres secteurs de haute précipitation et de sédiments déposés en couches, mais c'est mode de ruptures ont souvent été non reconnus. Les ruptures se produisent souvent cycliquement en raison du développement de sol au-dessus d'ensiène ruptures. Le drainage d'eaux souterraines des sédiments déposés en couches est la clef pour réduire le potentiel d'événements futur et a été employé avec succès pour réduire les chances de ruptures affectant des pipelines, des routes et des mines de gravier.

1. INTRODUCTION

Groundwater blow-off failures are common throughout western Canada and are an important geomorphological process in many areas. The failures tend to be cyclic, occurring at intervals of 20 to 40 years in many locations, and usually occur in areas of bedded sediments where beds of sand or silt interbedded with more permeable sand or gravel layers occur. Similar failures may also occur in areas of shallow soil overlying bedrock, particularly horizontally bedded bedrock.

2. FAILURE MECHANISM

Figure 1 shows a typical failure sequence based on observations of numerous events including observation of a few large failures as they occurred. Variations on this typical sequence are often seen.

The cycle of failure often starts with the development of vegetation on a slope underlain by bedded sediments (Figure 1A). Colluvial processes and vegetation growth result in mixing and weathering of a near surface layer of soil that may be 1 to 3 m deep. This near surface layer, which gradually becomes less permeable and thicker, impedes seepage drainage from the higher permeability layers within the bedded sediments.

As the seepage drainage from the permeable layers is increasingly blocked, groundwater storage in the permeable layers tends to increase, as does the groundwater pressure applied to the base of the lower permeability layer developed along the slope (Figure 1B).

Eventually, the groundwater pressures along the bottom of the low permeability layer may reach the point where the effective stresses along the bottom of the layer are close to zero (Figures 1B and 1C). In some cases, upward bulging of the surface layer indicates that the layer has been pushed up by the high groundwater pressures. In other cases, small translational sliding movements may occur prior to complete failure (and may sometimes facilitate drainage so that complete failure does not occur). High groundwater pressure conditions resulting in failure often occur during periods of high precipitation and runoff that cause increased infiltration on upland and adjacent areas.

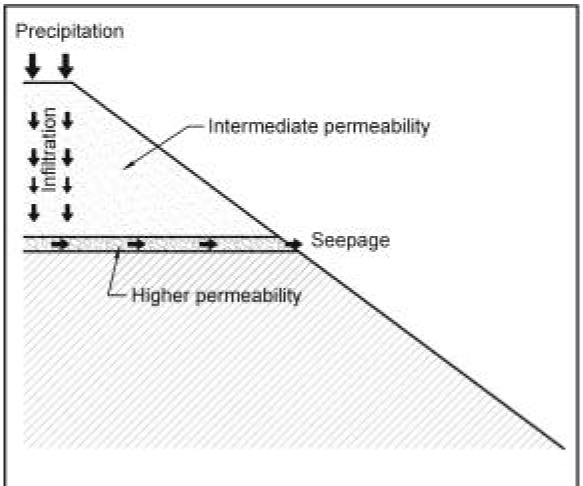

Figure 1A. Initial slope with drainage occuring from layer.

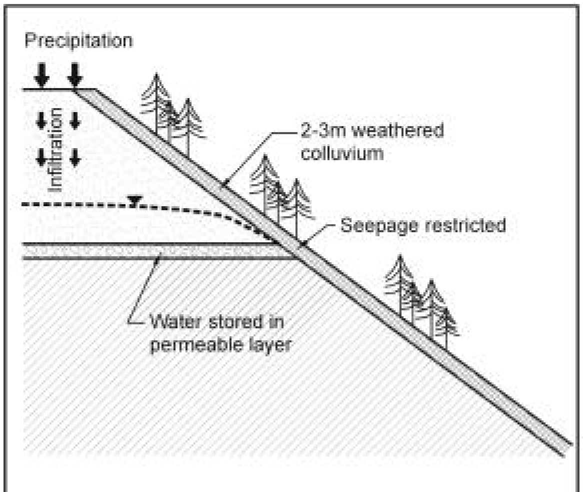

Figure 1B. Development of surface layer that restricts drainage.

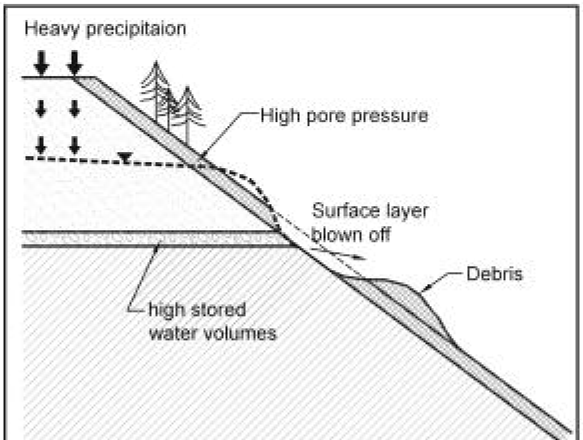

Figure 1C. High water pressures result in surface layer being blown off.

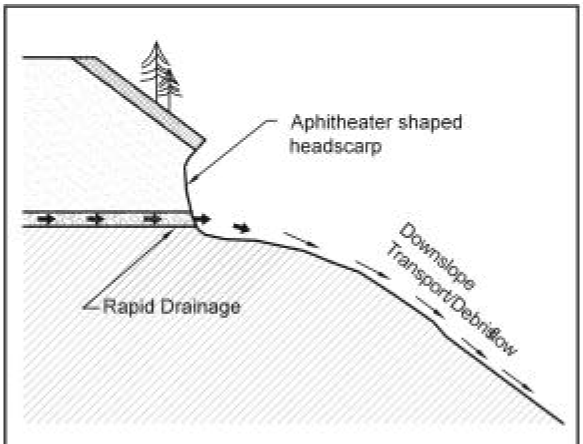

Figure 1D. Rapid drainage of groundwater causes erosion and piping and often a debris flow.

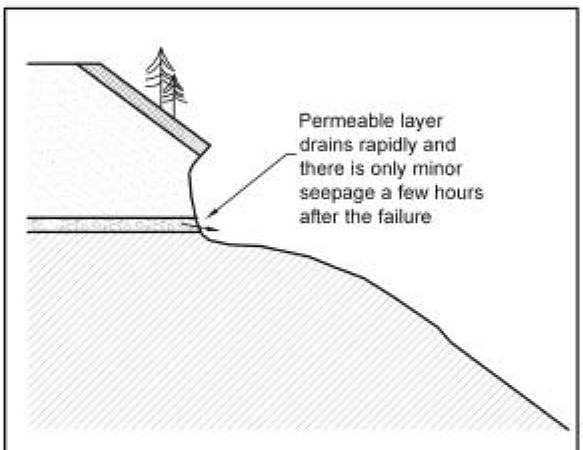

Figure 1E. A few hours to a day after the failure, there is usually almost no flow from the permeable layer.

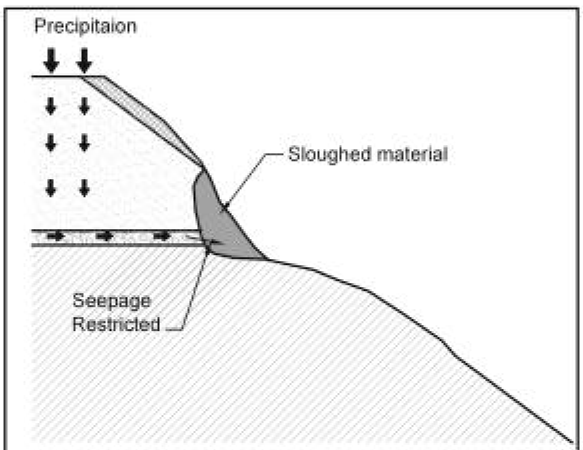

Figure 1F. After the failure, the oversteepened slopes slough in starting the cycle of drainage restriction again.

Figure 1. Schematic drawing showing cyclic development of a groundwater blow-off failure.

As a result of the high groundwater pressures, the surface layer may be blown off over a local area (Figure 1C) allowing rapid drainage of the stored groundwater to occur.

High drainage rates of large volumes of stored groundwater often result in retrogressive piping erosion of the bedded sediments (Figure 1D) forming an amphitheater-shaped depression with steep or overhung sideslopes. The elevation of the bottom of the basin is controlled by the seepage point(s). Large volumes of material may be eroded, creating a debris flow. A gully is often eroded down the slope below the failure by the high velocity debris flow. In other cases, the piping erosion erodes back into the slope and uphill, creating a deep ravine. Translational sliding of the oversteepened slopes around the amphitheater contributes further sediment that is transported downslope by the high drainage flows. The actual failure usually only lasts a few minutes to a few hours. It is important to note that in virtually all the failures observed, there was no appreciable surface flow into the head of the failure area.

After drainage of the stored groundwater is complete, there is usually very little seepage from the failure area and this seepage may be obscured in some cases by material that has sloughed from the sides of the amphitheater (Figure 1E). As erosion of the sides of the amphitheater occurs and vegetation grows on the area, the cycle of failure often repeats over a period of years (Figure 1F). The reoccurrence interval varies depending on precipitation patterns and growth rates, but in coastal BC may be on the order of 20 to 60 years, based on apparent tree ages, and in the interior may be somewhat longer in some areas.

While the low permeability layer that restricts seepage frequently develops as a result of vegetation growth and near surface colluvial processes, other mechanisms to restrict drainage are possible. A few failures have been observed where seepage was restricted by freezing. In other cases, sloughed material may be sufficient to restrict drainage.

Once failure occurs, the area immediately adjacent to a failure may be less prone to future failures in the short term since drainage from the permeable layers can occur. Over time, as the headscarp area sloughs, vegetation growth becomes established and high precipitation events occur, the likelihood of failure increases once again. On many slopes, there are old gullies, old debris flow areas and old amphitheater shaped head scarp areas of various ages created by repeated failures.

The volume of material involved in the failure may range from a few cubic meters up to extremely large failures such as those that have occurred along the Coquitlam River on both natural and artificial slopes.

3. CONDITIONS REQUIRED FOR FAILURE

The following conditions are required for blow-off failures to occur:

1. Slope angle: Based on observation, slope angles typically range from approximately 20 to 25° up to 38 to occasionally 45°. If the slope is too flat, the soil layer will not slide off and allow rapid drainage. Also, as a practical observation, the runout angle of the saturated silt, sand and gravel is frequently between 14 and 17°, imposing a further lower bound on the required slope angle. At the upper end, development of a colluvium layer will not occur if the slope is too steep (the layer tends to slide off as it forms). Typically, the maximum slope angles on which a colluvial and soil layer can develop are around 36 to 45°. At the steeper slope angles, the soil layer may slide at lower water pressures, preventing the development of large stored volumes. The most frequently observed natural slope angles have been around 25 to 32°.
2. Stratigraphy: Usually bedded sedimentary conditions with anisotropic permeability conditions including at least one layer of higher permeability and sufficient lateral extent so that large volumes of groundwater can be stored. The higher permeability layer is often sand and gravel or gravel. In some cases, fractured bedrock provides the permeable horizon.
3. Infiltration: Sufficiently permeable overlying materials overlying the high permeability layer so that recharge can occur. The overlying layers are often sand. Infiltration conditions may be enhanced in some cases by disturbance of the surface or surface ponding.
4. Precipitation conditions: Periods of high precipitation or runoff that result in high infiltration, raising groundwater pressures to the point that failure occurs.

It is stressed that surface water flow into the failure area is not required and close examination of many failures shows that in virtually all cases, there was no appreciable surface water flow into the failure area. Also, the direction of groundwater flow is more or less horizontally out of the slope, not parallel to the slope.

4. CASE EXAMPLES

The following case examples illustrate various types of groundwater blow-off failures that have been observed. The examples include both “text-book” cases and failures that have occurred under conditions that vary from those discussed above. Most of the case histories discussed tend toward the larger failure sizes since it is often difficult to photograph the smaller ones that are usually surrounded by dense woods.

4.1 Stone Creek

Figures 2A and 2B show a blow-off failure that occurred near Stone Creek south of Prince George near a pipeline route. The failure occurred within a wooded area and while the pipeline right-of-way was covered with the failed debris, the pipeline itself was not a cause or trigger of the failure. The failure initiated near the mid-point of slopes that were approximately 90 m high at angles of 25 to 30°. Debris from the failure was washed out onto lower angle slopes (a colluvial apron from previous failures) near Stone Creek. There was a clearcut on the flatter slopes above the failure, but this was probably not a major factor in the occurrence of the failure since there were numerous old gullies across the slopes produced by previous blow-off failures. Prior to the blow-off failure, there were evidently some translational movements of the surficial layers since there was some vegetation growth on the upper part of the failure scarp.

The exposures in the area included bedded glaciofluvial deposits including silt, sand and gravel with some till. As shown on Figure 2B, the upper end of the failure was amphitheater-shaped and was located at the top of an old gully formed by a previous failure. There were several layers from which seepage occurred during the failure and there were piping holes visible at several points around the head scarp area. The debris from the failure ran down the slope and gully as a debris flow and accumulated on a colluvial apron near the creek. The timing of the slide may have been related to an increase in surface infiltration as a result of a forest fire on the upland area above the slide two years prior.

The failure could have exposed the pipeline, but did not. Also, the generation of sediment from the area, while natural, was a concern to local regulatory personnel. As indicated, the failure was a natural event with no connection to the pipeline. Ongoing groundwater drainage was provided by hand digging a hole and installing a treated timber crib surrounded by non-woven filter cloth and drained by a culvert to provide ongoing drainage from the seepage layers. Additional drainage has recently been installed in nearby areas.

4.2 Coquitlam Valley

The Coquitlam River valley is located northeast of Vancouver, BC. Deposits in the Coquitlam Valley consist of a complex series of alluvial, glaciofluvial, glaciolacustrine, glacial till and periglacial deposits formed during multiple glaciations. Along the lower parts of the valley, large sidehill gravel pits have been excavated in the extensive sand and gravel deposits. Groundwater piping was widespread along the lower parts of the slopes where blow-off failures did not occur. The discussion of the failures is based on conditions in the early 1980's prior to recent extensive work to stabilize the slopes. Evans and Savigny, 1994 have also briefly discussed failures in the Coquitlam area that they termed seepage erosion or caving erosion failures.

The failures discussed in this section occurred in the gravel pits on both natural and excavated slopes and as natural slides from both sides of the valley near and downstream of the Coquitlam Dam, upstream of the areas of gravel mining. The valley is approximately 130 m deep with steep lower slopes and moderate to gentle upper slopes.

Several of the blow-off failures on and near the steep mined slopes retrogressed back into the slope to form large ravines (Figures 3A to 3D). The failures in the gravel pits have ranged up to several hundred thousand cubic meters in single failures. Large ravines were eroded during single events. Unlike many of the other failures discussed in this paper, the low permeability surface zone on the mined slopes was formed by colluvium and in many cases there was no substantial vegetation development. In some cases, the failures resulted from extremely high infiltration rates and the drainage reduction due to surficial sloughing. Freezing of the surface may have been a factor in a few cases.

Failure and development of one of the gullies was observed from a helicopter during a high precipitation event. During the failure, head of the gully (amphitheater area) was retrogressing at several meters per minute and the gully below the failure was transporting a mixture of sand, gravel and water 20 m wide and perhaps 10 m deep at a several meters per second.

Several of the gullies that formed in the gravel pits retrogressed along the centerlines of ridges, which is not where gullies would normally be expected to form. However, old logging roads also followed the ridges. These roads were constructed by grading through the surface layers to depths typically of 0.5 to 0.8 m. It appeared that greater infiltration was occurring along the old roads, resulting in groundwater mounding under the ridges. Two of the gullies that formed followed bends in the logging roads when there was no other obvious reason for the gully to bend 90°.

Failures on natural slopes in the Coquitlam River valley have included a large failure (300,000 m^3) on the west side of the river that blocked the river in 1952 (Evans and Savigny, 1994). This failure is noted as having an amphitheater shaped head area and imay have been a blow-off failure. Recent work has shown that there also are a number of smaller blow-off failures on natural slopes on the east side of the valley near the Coquitlam Dam.

4.3 Chamberlain Creek, Sukunka Valley

Figures 4A to 4E show a groundwater blow-off failure and debris flow that ran a total of 300 m vertically (800 m along the slide path) down 25 to 30° slopes on the south valley wall of the north branch of Chamberlain Creek south of Chetwynd. Geological conditions in the area consist of 1 to 4 m of clayey silt till with numerous rock fragments overlying horizontally bedded Moosebar Formation shales and Gething Formation sandstone, coal, shale and conglomerate. Most of the slide path was underlain by the Gething Formation and the upper end of the slide was close to the contact with the overlying Moosebar Formation.

Unlike the "text-book" failures discussed above, the groundwater accumulation occurred in shallow rock that limited the depth of failure. Also, unlike many of the slides overlying surficial materials, there were several seepage points into the slide. Additional seepage probably occurred along the slide path as the slide eroded the surficial materials down to or close to bedrock. The seepage may have been controlled by more permeable beds within the Gething Formation.

There were several old failures on the slope (Figure 4A) that predated construction of an access road switchbacked across the slope. The failure under discussion initiated above the road switchbacks and traveled across two road segments on the slope. As shown on Figure 4B, there was no surface water flow into the head of the slide.

The main area of initiation had a rounded headscarp (Figure 4C). Two days after the failure occurred, there was still locally appreciable amounts of seepage issuing from the rock. Development of a full amphitheater shaped depression did not occur since the shallow rock restricted downcutting erosion. There were several seepage areas in the headscarp area and there was a narrower retrogression upslope from the area shown in Figure 4C (above the logs shown in the figure) where there was another area of seepage. Several bulged areas were found on nearby slopes by probing with a hand auger. These areas had voids above the bedrock surface where the pore pressures under the till and root mat had evidently been high enough to push the soil upward, but not quite high enough to blow it off.

The flow traveled at high velocity, especially in the upper part of the failure. Where it crossed the first logging road switchback, the slide evidently jumped off the road fill and trimmed branches off trees and snapped a tree to elevations 10 m above the local ground surface (Figure 4D). Where the slide crossed the two road switchbacks, large amounts of wood debris and water were deposited on and diverted down the roads. Farther downslope, at a bend on slightly flatter terrain, the slide velocity was estimated at 20 m/s. This velocity was probably lower than higher up the slope.

Along most of the slide path, the slide debris ran down a gully that was typically 10 to 15 m wide with steep sideslopes (Figure 4E). It is not clear whether the slide followed an existing gully formed by past events and cleaned it out, or whether the slide eroded a new gully. However, in view of the other old failures on the slope, it is likely that at least part of the gully had been formed by similar previous events.

5. CONCLUDING REMARKS

Blow-off failures are widespread a common geomporphological mechanism on slopes throughout BC and in many other areas. Conditions required for failure include high precipitation, bedded sediments with layers of high permeability or fractured rock, and conditions that restrict seepage drainage such as a reworked/weathered surficial soil layer and root mat. One of the interesting attributes of the failure mechanism is the very large quantities of groundwater that drain from the seepage zone over a short period of time. These high seepage flows often result in debris flows and/or substantial amounts of piping erosion.

The failure mechanism has sometimes been misinterpreted. Important points to note include:

1. The direction of seepage is out of the slope, not parallel to the slope as has sometimes been conjectured during geomorphological studies of similar failures.
2. There are normally not significant surface water flows into the headscarp area and surface water flow is not required. Very high flows usually occur during drainage of the stored groundwater. After the failure, the seepage zone may he difficult to identify due to sloughing and the very low seepage rates prevailing after drainage has occurred.
3. Frequently, there are old blow-off failures of various ages throughout the area and the failures tend to reoccur over time. Failure cycle often occurs at intervals of 20 to 80 years, depending on the area.
4. Conventional debris flows involving mobilization of accumulated material along a creek channel are widespread. However, debris flow failures formed as a result of blow-off failures are primarily generated by stored groundwater draining rapidly down the slope. In some cases, additional water may enter from seepage zones lower down along the channel. In a few cases, tributary flows have contributed additional water farther down the channel; however, this is not typical.

Areas prone to these events can be recognized on airphotos via the debris flow run-out tracks and gullies and the amphitheater-shaped depressions. Blow-off failures have been identified throughout western Canada and probably occur elsewhere under similar conditions. Bedded glaciofluvial sediments along valley slopes and terrace fronts may be particularly susceptible to such failures. Groundwater drainage can be used to prevent build-up of large volumes of stored groundwater and is the key to reducing the potential for future events. Relatively small drainage works have been successfully used to reduce the chances of blow-off failures affecting pipelines, roads and gravel mines.

References

Evans, S.G. and Savigny, K.E. (1994) *Landslides in the Vancouver-Fraser Valley-Whistler Region,* in GSC Bull. 481, J.W.H. Monger, ed.

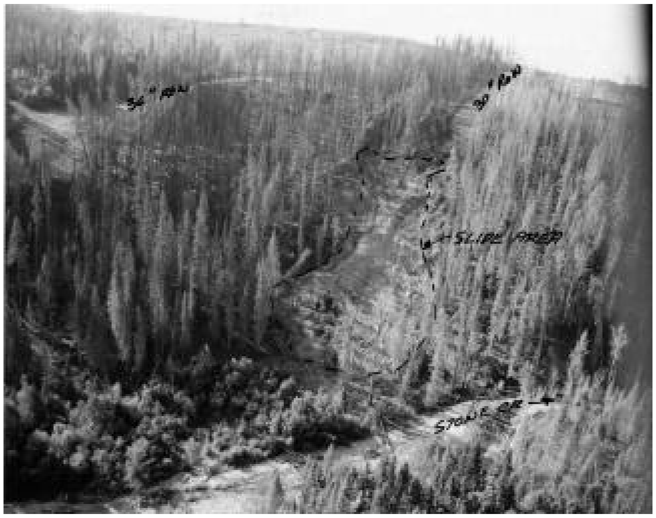

Figure 2A. Aerial view of a blow-off failure at Stone Creek that was located in ridged ground resulting from previous failures. The initiation of the failure was at the mid-point of the slope. There was no surface flow into the failure. The debris ran out onto the lower part of the slope.

Figure 2B Detail showing the crest of the Stone Creek failure. The main seepage exit was below the colluvium and slough in the lower part of the photo. Some of the cavities left by soil piping above the main seepage area are visible just above the sloughed material. There was evidently a small amount of translational movement prior to the failure since there were a few small plants growing on the upper part of the failure scarp. Drainage was installed by digging down through the sloughed material.

Figure 3A (left) Oblique view of gully formed in sandy glacial drift overlying bedded sands and gravels with occasional silt layers in a gravel pit along Pipeline Road, Coquitlam (photo taken around 1984). The amphitheater shaped bowl with steep sideslopes at the head of the gully is visible behind the pinnacle at the right side of the photo. This gully eroded back into the ridge over a few hours.

Figure 3B (right) Crest area of a blow-off failure that eroded a steep gully downslope of the failure. This failure occurred on an oversteepened face formed by excavation. The restraining layer may have been formed by natural permeability variations and sloughing rather than vegetation growth. The groundwater induced piping started high up on the face and undermined a root mat remaining after the bench had been logged. Subsequent sloughing of the oversteepened slopes in the crest area (shadowed area) covered the seepage point.

Figure 3C (above). Looking upslope along the eroded canyon at the headscarp area of a blow-off failure along Pipeline Road (photo taken around 1984). The amphitheater shaped head area with oversteepened slopes is visible. There appeared to have been two main seepage points (shown on photo), resulting in a stepped profile. Similar to most of the groundwater blow-off failures observed, there was no significant surface water flow into the gully and much of the volume of the gully was eroded over a single short period. Some of Pipeline Road failures later retrogressed in subsequent cycles of failure as a result of seepage egress being blocked by sloughed material.

Figure 3D (above). Looking upslope along a very large gully initially formed within a 24 hour period by retrogressive erosion during a blow-off failure. The head of the gully is in the background of the photo, visible through the V-shaped gully in the foreground. In the 1960's to early 1980's, some very large gullies were formed over very short time periods by groundwater blow-off mechanisms followed by soil piping and erosion.

Figure 4B (above). Headscarp of failure showing several seepage areas (arrows) from shallow bedrock. There was no surface flow into the slide area. The logs were at a step where there was an additional smaller failure immediately upslope.

Figure 4A (left). Debris flow failures above Chamberlain Creek are indicated by arrows. The center failure is discussed in the text. The other two failures are old ones that predate the construction of the access road. The failure occurred on slopes of 25 to 30° and ran a lineal distance of over 800 m down to the creek.

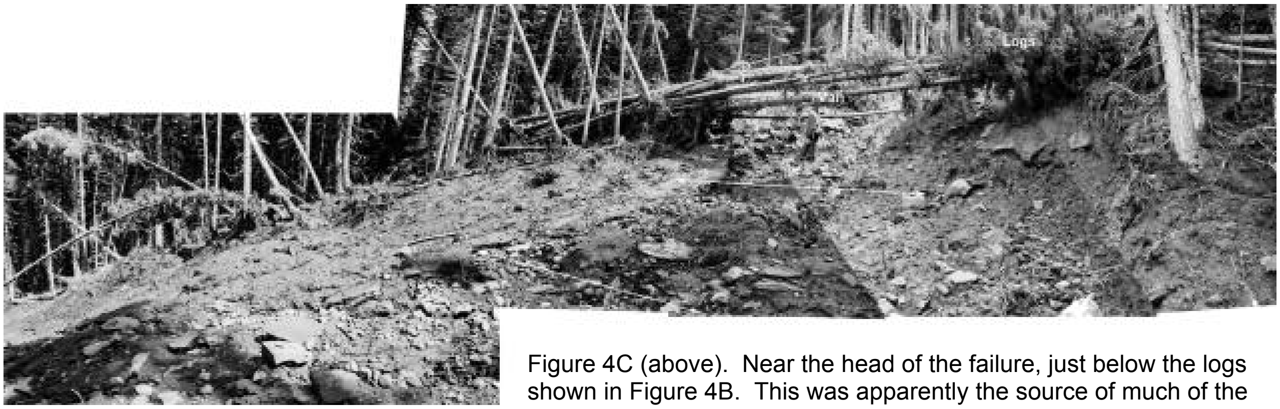

Figure 4C (above). Near the head of the failure, just below the logs shown in Figure 4B. This was apparently the source of much of the seepage outflow, although the failure retrogressed higher up the slope beyond the logs. The double headed arrows across the slope show some of the main seepage horizons. A man standing under the logs shows the scale. Photo 4D below was taken 175 m downslope from the location of this photo

Figure 4D (left). Looking downslope where the slide crossed a logging road switchback. The high velocity of the debris flow at this point is shown by the trim lines on the trees (arrows) which were almost 10 m above the ground. The debris flow evidently jumped off the road at this point (like a ski jump), accounting for the trim lines. Note also the tree that was snapped off near the same elevation at the right of the photo. The main slide path downslope of the road was 10 to 12 m wide at an overall slope of 23°. A large amount of woody debris was deposited behind the photographer on the road.

Figure 4E (left). Looking downslope at the first major bend. Note the man circled in the background for scale. There was a seepage area in the foreground that contributed additional water. As the slide eroded the surficial materials along its path, additional seepage occurred from the bedrock and probably increased the volume of the flow.

The bend was 57°, with an estimated radius of curvature of 60 m and the super-elevation was estimated to be 2 m, indicating a velocity of 20 m/s. The velocity here may have been lower than at the logging road in Figure 4D since a large amount of water and debris was diverted where the slide crossed the road.