Stability of permafrost slopes in the Mackenzie valley

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Abstract: Slope stability is conventionally analyzed in terms of a 'factor of safety', that is, the ratio between the shearing strength of a material forming a slope and the forces tending to cause sliding or failure of that material. In permafrost regions, many failures are triggered by a decrease in strength of frozen ground due to excessive thawing and deepening of the active layer. This results in an active-layer detachment. This type of slide is often triggered by excessive thaw following the destruction of surface vegetation by fire. The most likely impact of climate warming may be an increase in active-layer detachments if there are more fires. Although most of the deeper rotational failures occur along river banks where erosion at the foot of the slope is an important factor, long-term decreases in permafrost thickness could also contribute to instability.

Résumé : Par convention, la stabilité des versants est analysée en fonction d'un « facteur de sécurité », c'est-à-dire du rapport entre la résistance au cisaillement des matériaux qui constituent un versant et les forces qui ont tendance à causer des glissements ou des ruptures dans ces matériaux. Dans les régions pergélisolées, de nombreuses ruptures sont déclenchées par un abaissement de la résistance du gélisol à cause d'un dégel excessif et une augmentation de la profondeur du mollisol. Il en résulte un décollement du mollisol. Ce type de glissement est souvent provoqué par un dégel excessif attribuable à la destruction de la végétation par un incendie. La répercussion la plus probable d'un réchauffement climatique pourrait être une augmentation des décollements de mollisol associés à une augmentation des incendies. Même si la plupart des ruptures rotationnelles profondes se produisent le long des berges des cours d'eau, là où l'érosion au pied des versants est un facteur important, les diminutions à long terme de l'épaisseur du pergélisol pourraient concourir davantage à l'instabilité des versants.

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INTRODUCTION

Approximately 2000 landslides in the Mackenzie valley between Inuvik and Fort Simpson and about 1000 in the ground-ice rich coastal uplands near the Beaufort Sea have been mapped from airphotos (*see* Aylsworth et al., 2000). This abundance of slides in a permafrost region with abundant ground ice suggests that thawing of this ice plays a role in landslide occurrence. Therefore, climate warming becomes an additional factor contributing to slope failure in this region because of the potential it holds for melting ground ice. This paper examines how permafrost slopes in the Mackenzie valley fail and analyzes the sensitivity of slopes to factors controlling slope stability.

Whereas another paper in this bulletin (Aylsworth et al., 2000) on landslide distribution gives a comprehensive classification of landslides, this paper concentrates on two mechanisms which often initiate slope failures in or on permafrost in the Mackenzie valley: deep seated rotational failures and active-layer detachments (Aylsworth et al., 1992). Rotational slides involve failure through permafrost and may be triggered by a decrease in permafrost thickness. Active-layer detachments form along the top of permafrost and are triggered by excessive amounts of water produced by rapid or particularly deep active-layer development in ice-rich ground. Both types of failure often evolve into more complex features as thawing of the slide mass or adjacent exposed ice-rich sediment continues.

DEFINITION OF SLOPE STABILITY AND FACTOR OF SAFETY

Landslides occur because the forces resulting from the weight of the material forming the slope overcome the shear strength of that material. The conventional engineering approach to assessing the stability of a slope is to compare these two opposing factors. The proportion by which the strength exceeds the forces tending to overcome this strength gives a measure of the stability and is termed the 'factor of safety' against failure (FS):

$$FS = \frac{\text{Strength of slope material}}{\text{Shear stress acting along failure surface}}$$

If FS is greater than 1, the slope is stable; if equal to or less than 1 it is quasi-stable or unstable and should fail.

Determining the forces due to the weight of material is the easiest part of a stability prediction because soil or rock unit weights can be accurately measured and variability in unit weight can be assessed from surface samples or compiled from boreholes. Accurately determining soil strength and the location of the surface along which failure will take place is much more difficult. Laboratory techniques for measuring material strength are routine, but the accuracy with which the results represent the strength mobilized in the ground is difficult to know. Furthermore, the position and shape of the failure surface along which this strength is mobilized must be estimated. Without other constraining information it is usually chosen as the surface calculated to give the lowest factor of safety. Finally, the presence of water in the slope material is fundamental to determining stability. Pressure in soil pore water can be high enough to counteract the weight of overlying material and eliminate the friction which may be maintaining the slope. This factor is particularly important in ice-rich ground where thaw can produce considerable quantities of pore water. Uncertainties in the magnitude or nature of these variables lead to the selection of safety factors considerably in excess of 1 when slopes must be designed as part of an engineering project.

LANDSLIDE MECHANISMS

'Rotational slides' involving deep-seated failure in rock or Quaternary sediments form along concave or dish-shaped failure surfaces. The slide mass rotates as a rigid body, leaving a headscarp steeper than the original slope. The lower part of the slide mass usually moves out onto the base of the slope. The factor of safety against this kind of failure is customarily determined by representing a slope by a single vertical cross-section. This approach simplifies the problem by implying that the cross-section is representative of the wider section of slope which will almost certainly be involved in a failure. The simplest analysis assumes a circular failure surface. The slide mass rotates as a rigid body without undergoing any internal deformation, requiring only the shearing along the failure surface to be considered in the factor of safety analysis. Also, the analysis only predicts initial slope failure; it does not provide any indication of how far the slide mass will move down the slope.

Failure usually begins as a rigid body movement with internal deformation of the slide mass occurring once the toe moves out beyond the base of the initial failure surface (Fig. 1). In an extreme case, slide masses may become completely fluidized due to high moisture contents and melting ground ice and move easily on angles much less than that of the initial failed slope. This results in a complex failure in which the fluid behaviour can modify considerably the initial rigid form. While prediction of fluid movements is more difficult, some indication of subsequent movement will be given by sediment consistencies, ice contents, and length and steepness of slopes beneath sites of initial failure.

The other failure mode discussed is the 'active-layer detachment'. This involves only the active layer with the failure surface determined by the boundary between thawed and frozen sediment. Stability can be analyzed by the infinite slope method. With this technique, the failure surface is considered as a planar surface that is long compared to the slide thickness. The added resistance where the failure surface cuts across this thickness can thus be neglected. The mat of living vegetation and roots that usually exists at the ground surface can be the strongest part of the slide mass and is often found compressed and crumpled at the base of a slide. This kind of slide may deepen and lengthen if thaw continues into ice-rich ground exposed by the original slide (Fig. 1). If this happens, it becomes a retrogressive thaw flow.

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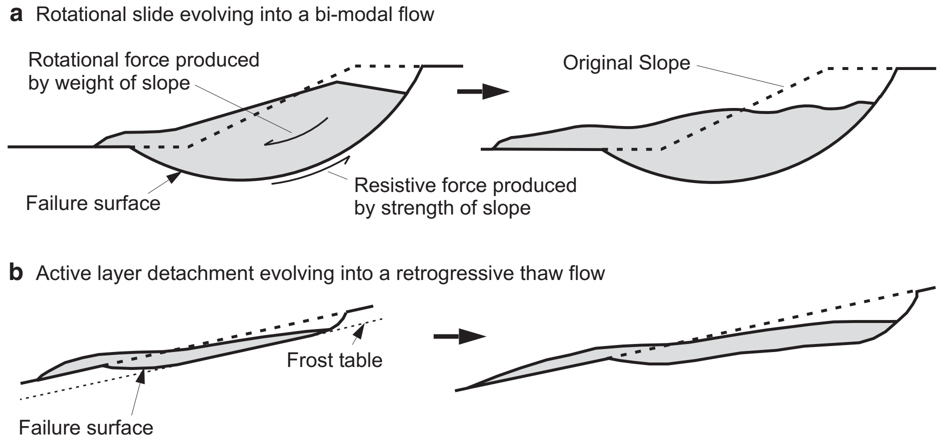

Figure 1. Two primary types of landslides occurring in permafrost in the Mackenzie valley. ***a****) Deep-seated rotational slides take place where a frozen layer cannot be supported by an underlying weaker material. This kind of slide may evolve into a flow if the slide mass is ice-rich.* ***b****) Active-layer detachments take place where an excessively deep thaw encounters ice-rich ground. Deep thaw may be caused by a particularly warm summer or the destruction of insulating surface vegetation. If thawing continues to encounter ice, a retrogressive thaw flow may develop.*

TRIGGERING OF SLIDES

Factors of safety are only as accurate as the strength and weight measurements used to calculate them. Because of this uncertainty, a slope that is stable according to the calculated factor of safety can still slide. Therefore, it may be more useful to recognize situations where the factor of safety will be reduced. If an ice-bonded layer thaws or a slope is undermined by river scouring, strengths will decrease or forces will increase. While the factor of safety may be uncertain, these situations are definite indications that stability is deteriorating. Eventually, the factor of safety may drop below 1. There are a number of processes which may trigger slides and the sensitivity of slopes to strength or loading changes caused by these processes will be discussed with respect to specific features.

ROTATIONAL SLIDES

Large rotational landslides are common along the Mackenzie River and some major tributaries. They occur in banks where these streams have cut through glaciolacustrine sediments or into poorly indurated rocks, such as the Cretaceous shale units along the Peel River and its tributaries. Banks can be 60 m or more high. Undercutting by scouring and toe erosion, especially on bends, maintains slopes close to the angle of repose where cohesionless sands and gravels are encountered. Although scouring may be a triggering mechanism, especially if undermining occurs, other processes can contribute to reducing the factor of safety. In the case of rotational slides, a decrease in the thickness of ice-bonded sediment or an increase in pore-water pressures beneath ice-bonded sediments will accomplish this. Therefore steepening of the slope angle by river scouring may, by itself, be insufficient to initiate a slide. Other processes occurring in conjunction with toe erosion may actually trigger a slide.

The response of the factor of safety to changing slope conditions can be studied by varying those conditions and noting how the factor of safety responds; however, to perform this type of analysis, the strength of the sediments forming the slope must be known. An added complication is the scarcity of strength determinations on frozen sediments. An example of how this difficulty can be overcome is given by analyzing a recent rotational slide near the mouth of Mountain River (Fig. 2), a location where slope stability investigations have previously been undertaken (McRoberts and Morgenstern, 1973, 1974a).

Immediately upstream from the mouth of Mountain River, the outside of a broad bend impinges against a slope cut into glaciolacustrine and glaciofluvial sediments deposited in glacial Lake Mackenzie (Smith, 1992). Almost the entire bank for several kilometres upstream exhibits slope failure (Fig. 3). Most slides appear on the earliest air photography of the area (1950) but the recency of forest establishment on scars suggests that slides do not predate about 1900; however, two failures have occurred in the early 1990s. One has resulted from piping with subsequent subsidence of overlying frozen sediment (Burton et al., 1995). The other is a multiple rotational failure involving frozen sands overlying clays (Fig. 4).

The recent rotational failure occurs in a 50 m high bank and consists of three retrogressive blocks. The toe is outlined for about 300 m along the edge of Mountain River by a series of low upthrust ridges of clay. These upthrusts, together with

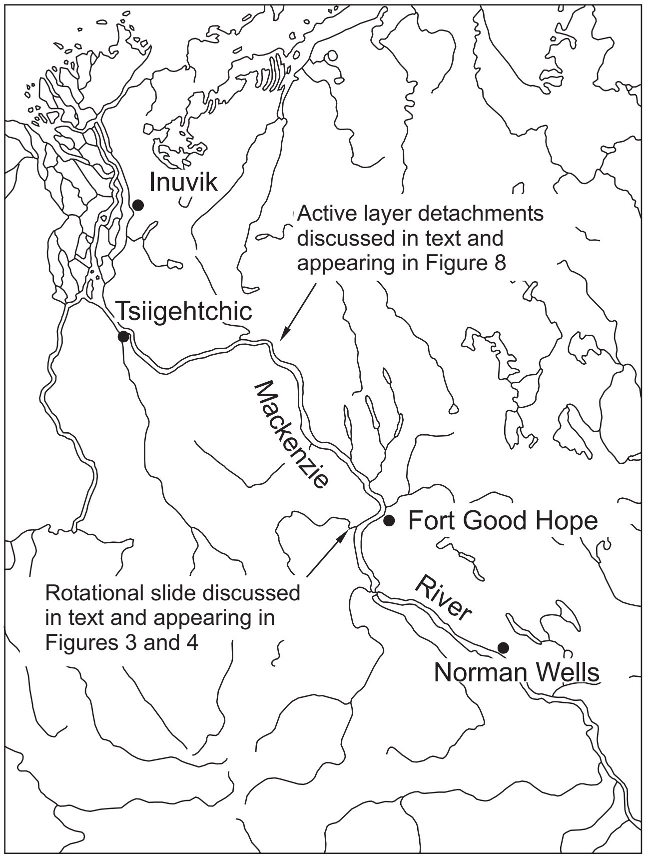

Figure 2. *Location of landslides discussed in detail.*

the obvious downdropping of the top of the slope and rotation of the blocks, indicate that the failure has occurred along a curved surface extending from the main headscarp to a considerable depth below river level, then returning to the surface at the upthrust ridges. The position of the toe and the headscarp, together with the headscarp angle enables the

Figure 4. *Rotational failure near the mouth of Mountain River. Slump blocks, consisting of deltaic sands deposited in glacial Lake Mackenzie by the ancestral Mountain River, are indicated by the patches of tilted forest. The headscarp, rotation of blocks, and river-edge uplifting of sediment all imply a circular failure surface that extends well into unfrozen clays below river level. Photograph by L.D. Dyke. GSC 2000-035A*

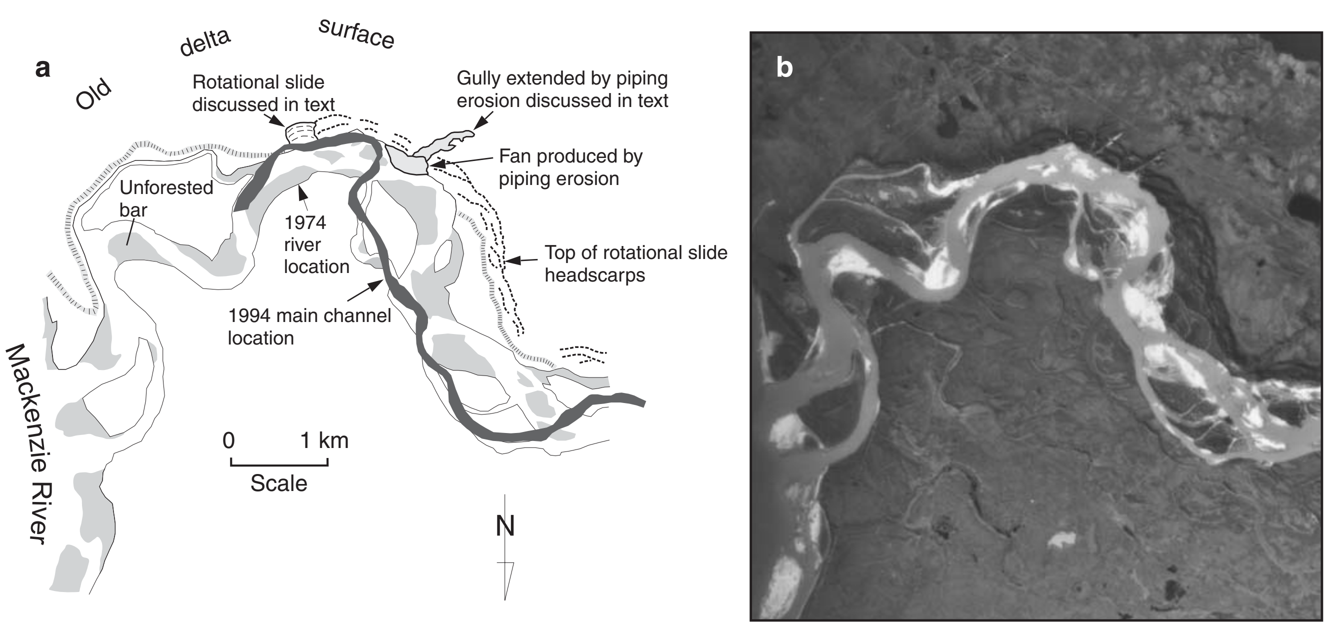

Figure 3. a*) The lowest reaches of Mountain River as traced from the adjoining* ***b****) 1974 airphoto (NAPL A21528-223) and the main channel position in 1994. Continual scouring over this time interval has probably triggered the rotational slide discussed in the text. Hence, stability in part depends on channel changes in the river. This situation is typical where tributaries and the Mackenzie River are incised into glaciolacustrine sediments. Deep-seated rotational slides are favoured because of the weakness of unfrozen clays which typically underlie frozen sands.*

failure surface to be located if it is assumed to be an arc of a circle (Fig. 5). With a failure surface specified, strength at failure can be estimated.

Failure strength of slope materials

The failure strength of geological materials consists of a frictional and a cohesive component. The 'frictional component' is a measure of how abruptly an increase in weight on the potential failure surface increases the resistance to movement. It can be likened to the angle (ϕ) required to initiate sliding of a block down a slope. The weaker the frictional component, the lower the angle required for movement. If the pressure of water occupying the pores (pore-water pressure) of a soil rises towards the pressure from the weight of overlying soil, the frictional strength will tend toward zero (ϕ = 0), reducing the factor of safety and making failure possible on increasingly shallow angles. The 'cohesive component' is the strength imparted by bonding or cementation between mineral grains of the soil. Cohesion is usually low for coarse-grained glacial sediments, i.e. sands and gravels.

At the Mountain River site, glaciofluvial sediments, consisting primarily of sands, overlie glaciolacustrine clay. The sands are frozen to a depth of 50 m (McRoberts and Morgenstern, 1974a), leaving unfrozen sand and clay below this depth. Clay is exposed only at river level but is thought to extend to the depth reached by the failure surface. This stratigraphic sequence is consistent with the regional stratigraphic character of glacial Lake Mackenzie sediments (*see* Smith, 1992). The low strength of the unfrozen clay under the frozen sand permits the slope to fail. If both the sand and the clay were frozen, failure at this site would be very unlikely.

If the strength of the sand and the clay are known, then the sensitivity of the slope to changes in permafrost thickness can be determined. The values shown in Table 1 below have been assumed, measured, or calculated.

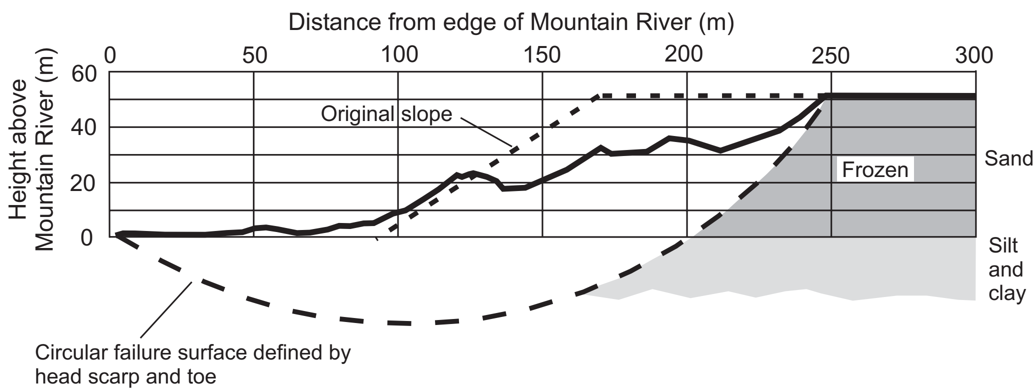

Figure 5. *A topographic profile of the Mountain River slide, surveyed in 1992, and the probable location of the main failure surface. The failure surface is defined by the location of the headscarp, the location of uplifted clay at the river edge, and the angle of the failure surface at the headscarp as implied by the location of slump blocks.*

Table 1. Values for strength components used in the stability calculation for the Mountain River site.

Material	Strength component	Description
Unfrozen clay	Frictional component	It is assumed that ϕ = 0. Although ϕ is probably higher than this, a low value is likely, otherwise failure would not be possible along such a deep surface.
	Cohesive component	Measured at the Mountain River Slide on exposed unfrozen clay: 600 lb/ft^2 (0.29 kg/cm^2).
Unfrozen sand	Frictional component	It is assumed that ϕ = 30°, a typical value for sand.
	Cohesive component	Assumed to be 0 because sands usually have little or no cohesion.
Frozen sand	Frictional component	It is assumed that ϕ = 30° because the friction should not be appreciably affected by the ice bonding and 30° is a typical value for unfrozen sand.
	Cohesive component	Calculated by finding the value that will maintain the slope at FS = 1 for the failure surface shown in Figure 5: 11 000 lb/ft^2 (5.4 kg/cm^2).

The cohesion of the frozen sand is found by conducting a stability analysis for the slope and stratigraphy shown in Figure 5. It is the only component of strength for which a value has not been assumed or measured. The cohesion of the frozen sand is determined by submitting trial values for the stability analysis until a value of FS = 1 is reached. Its value, as determined by this method, is listed in Table 1.

Sensitivity of slope stability to changes in slope conditions

The results of the strength analysis demonstrate that the frozen sands make by far the greatest contribution to stability at the Mountain River site. If bedrock occurred at river level, failure would be very unlikely. A factor of safety greater than 3 is indicated in Figure 6 for this case (i.e. depth of clay below river level = 0); however, the factor of safety rapidly decreases as the thickness of clay below river level is increased. This response points out the effectiveness of an underlying material with low strength in reducing the stability of an otherwise competent slope.

The importance of ice-bonding in maintaining stability suggests that stability is sensitive to thawing of ice-bonded permafrost. Climate warming might be expected to melt the top of an ice-bonded layer but groundwater flow beneath is also capable of transferring heat for thaw. Groundwater flow could dominate the thawing because this agent of heat transfer, in contrast to an air heat source, may act continuously in contact with the thawing surface; however, an analysis of this process would require knowledge of the degree to which climate warming would be reflected in groundwater temperatures.

The decrease in stability as permafrost thaws is shown in Figure 7. The figure is constructed on the basis that, before failure, the slope was barely stable (FS = 1) with permafrost at its present thickness. Without specifying whether thawing is taking place from above or below, it shows how the factor of safety decreases as permafrost in the sand becomes thinner. Plotting values of FS less than 1 shows that stability is quite sensitive to this change, suggesting that a few metres of thawing reduces the factor of safety appreciably. This analysis further suggests that slopes of this steepness and height were

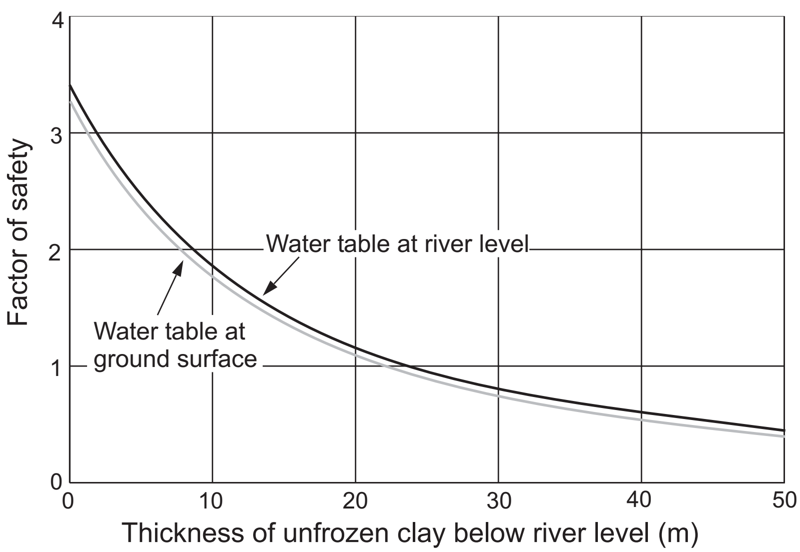

Figure 6.

The influence of unfrozen clay thickness below river level on slope stability at the Mountain River slide. Failure is very unlikely if competent bedrock lies immediately beneath the frozen sand; however, an increasing thickness of unfrozen clay reduces stability because a firm base is being replaced with a material having only a low frictional strength. Because the assumption of $\phi = 0$ implies a high pore-water pressure, it is almost equivalent to having the water table coincide with the ground surface. Therefore, the reduction in stability due to a high water table is small.

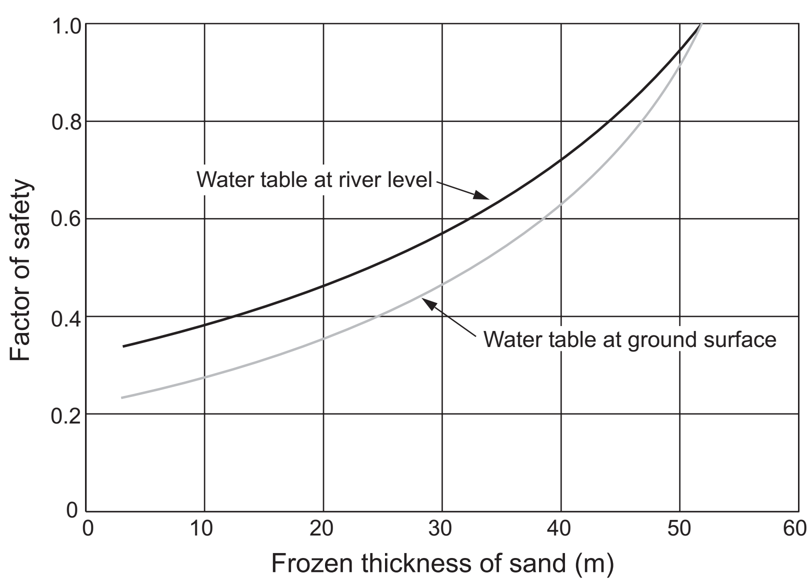

Figure 7.

*The influence of permafrost thickness on slope stability at the Mountain River slide. Decreases in thickness of 5–10 m, probable in the event of 4–5°C of warming in the mean annual air temperature over 50 years (*see *Burgess et al., 2000), would reduce stability. Groundwater pressure equivalent to the pressure with the water table at the ground surface would further reduce stability if thawing was mostly from the bottom up.*

entirely unstable before ice-bonding developed to the present depths. The present slopes may have been able to develop only after permafrost was established.

ACTIVE-LAYER DETACHMENTS

Failures allowing movement of the sheet of thawed sediment in the active layer are called active-layer detachments. Because they are difficult to detect on airphotos or they quickly evolve into retrogressive thaw flows, few are noted on the landslide distribution map in Aylsworth et al. (2000); however, they are probably one of the commonest types of landslide in the Mackenzie valley. Glacial and glaciolacustrine sediments are most susceptible to active-layer detachments, but weathered shale also exhibits this kind of failure. Once such a slide has exposed mineral soil, thaw will accelerate and reach greater depths than previously. If thaw continues into ice-rich ground, the original active-layer detachment may evolve into a retrogressive thaw flow where the slide deepens and develops a progressively thawing and retreating headscarp. This type of slide may not stabilize until the slide crater fills up with debris, the retreating headscarp reaches flat ground, or the scarp reaches ice-poor sediments.

The most noteworthy feature of active-layer detachments is the low slope angle on which sliding can take place. Many failures occur on slopes of less than 15° and failures on slopes as low as 3° have been recorded. These low failure angles remained unexplained by conventional stability analysis techniques until the role of excess pore-water pressure from thawing ground ice was recognized (McRoberts and Morgenstern, 1974b). If, during the summer thaw, water from melting ground ice is produced more quickly than it can escape to the surface, then the pore water begins to support the weight of overlying thawed sediment and the pressure in this water rises. Ice in excess of that needed to just fill the sediment pores and a rapid thawing rate can result in the pore water carrying the entire soil weight and hence a total loss of friction. If there is little or no cohesive strength, then high pore-water pressures available from thawing excess ice can induce slides on very shallow angles.

Active-layer detachments are most likely to be triggered by an event or condition that permits excessive pore-water pressure to develop in the active layer. During freeze-back, the active layer generally becomes ice-rich near the top as moisture from deeper levels is drawn to the advancing freezing plane. During thaw, moisture may move downwards to refreeze in the lower part of the active layer or migrate into the top of permafrost, producing an ice-enriched zone at the base of the active layer or in the top of permafrost (Mackay, 1980). An excessively warm summer may cause a higher than normal rate of melting. In this situation, failure is more likely as thawing reaches the lower levels of the normal active layer or extends into the ice-rich permafrost. This is because of the increasing weight of thawed material available to overcome any cohesion of the ground.

The event most likely to trigger an active-layer detachment is a forest or tundra fire. The heat from the fire, although intense, is short lived and produces little or no warming at the frost table (Mackay, 1977). Destruction of ground-surface vegetation, underlying litter, and peat is by far the most important effect because of the loss of insulation that this causes. The active layer subsequently deepens, eventually reaching a new equilibrium. This may take several years if the sediment is ice-rich to a considerable depth. If an active-layer detachment occurs, the bare soil surface will result in even greater thaw. Eventually revegetation will halt and ultimately reverse this increase; however, the time taken for revegetation will depend on the extent of further instability (i.e. retrogressive thaw flows) that develops after the initial active-layer detachment.

Sensitivity to failure

The tendency for an active-layer detachment to form can be determined by the same approach that was used for the rotational failure. In the case of the active-layer detachment, the failure surface is idealized as an inclined plane of indefinite (or infinite) extent. The fact that the failure plane must start at the surface is often ignored because this simplifies the calculation of the factor of safety. There is a force required to rupture the surface vegetation mat but it is probably very small compared to the resistance to movement along the rest of the failure surface. As with the rotational failure, the infinite slope analysis requires that the cohesion and frictional strength of the sediment be known (Hanna and McRoberts, 1988). Frictional strength can be greatly reduced while ground ice is melting and this phenomenon has been taken into account by McRoberts and Morgenstern (1974b). They incorporate a term called the “thaw consolidation ratio” into their analysis. This ratio compares the rate of melting with the rate at which excess water pressure is dissipated. The higher this number, the more the frictional strength is reduced.

Most of the Mackenzie valley has probably been burned at least once in the last 200 years. Many areas burned within the last 30 years are visible from the Mackenzie River. To illustrate the sensitivity of permafrost slopes to active-layer detachments and discuss the affect of forest fire on the thermal state of the ground, an example of this type of failure from the Thunder River area (approximately midway along Mackenzie River between Tsiigehtchic (formerly Arctic Red River) and Fort Good Hope, Fig. 2) is analyzed. Thirteen hundred square kilometres of forest adjacent the Mackenzie River in this area were burned in 1986 and within one year had developed extensive active-layer detachments (Harry and MacInnes, 1988). Several of these have evolved into retrogressive thaw flows (Fig. 8, 9). Active-layer detachments also developed within weeks of the extensive fires in the Tulita (formerly Fort Norman) area in 1994 (Savigny et al., 1995).

An example of the consequence of burning the vegetation mat is shown in Figure 10. This example shows a one-year record of temperature at the base of the organic layers in adjacent burned and unburned sites in the Thunder River area. For

Figure 8. Active-layer detachment slide in the Thunder River area. Bare mineral soil has been exposed by the removal of a thawed layer approximately 1 m thick. Photograph by L.D. Dyke. GSC 2000-035B

Figure 9. Retrogressive thaw flow slide in the Thunder River area. Ice-rich sediment can be seen in the head scarp of the slide. Thawing of the ice causes the slide to deepen and extend uphill, at the same time providing water to fluidize the sediment. Continued thawing of ice-rich mineral soil exposed by an active-layer detachment causes this type of slide to develop. Photograph by L.D. Dyke. GSC 2000-035C

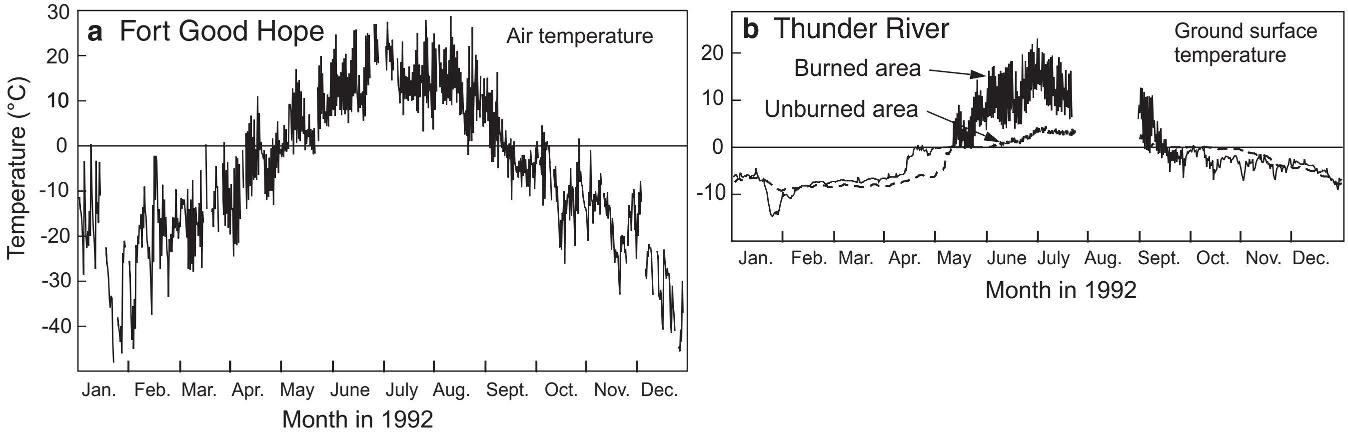

***Figure 10. a**) Air temperature record for Fort Good Hope in 1992 (170 km southeast of the Thunder River site) and **b**) simultaneous temperature records for the ground surface in burned and unburned areas at the Thunder River site. The ground surface receives about four times the thawing degree days received at the unburned site.*

the burned area, destruction of the organic cover was not complete, with a charred mat of mosses remaining. The unburned site is characterized by a moss, lichen, and dwarf shrub mat. Of course, the contrast in temperature between burned and unburned sites will vary depending on the kind and thickness of original vegetation cover and the degree of destruction. At Thunder River, the ground surface at the burned site is receiving about four times the degree-days of thawing received at the unburned site. A comparison of seasonal thaw calculated for these two environments is shown in Figure 11. This graph shows the progress of thawing based on the average temperature during the thaw season. Although the maximum thaw depth reached is accurate, the progress of thaw until this depth is reached will probably be different from that indicated on the graph. The rate of thaw will be determined by the temperature variability during the thaw season and the amount of ground ice present at different depths.

Both the increase in thaw depth and more rapid melting of ground ice on a burned slope will favour active-layer detachments. More rapid thaw will reduce friction and deeper thaw will increase the weight of material available to overcome cohesion. The sensitivity of slope stability to changes in these factors is shown in Figure 12. It gives the maximum slope angle that will be stable, depending on the depth of thaw and the amount of friction afforded by the soil. The other component of soil strength, cohesion, was determined in the same way that the cohesion of the frozen sand at Mountain River was determined. An active-layer detachment with known slide thickness and slope angle was chosen and the cohesion required to just balance the force causing failure was calculated. This requires an assumption about the frictional component of strength to be made. Considering that ground ice is abundant in the tills of the area and these materials contain approximately 25% clay, the likelihood is great that enough meltwater could be retained within the soil to support the

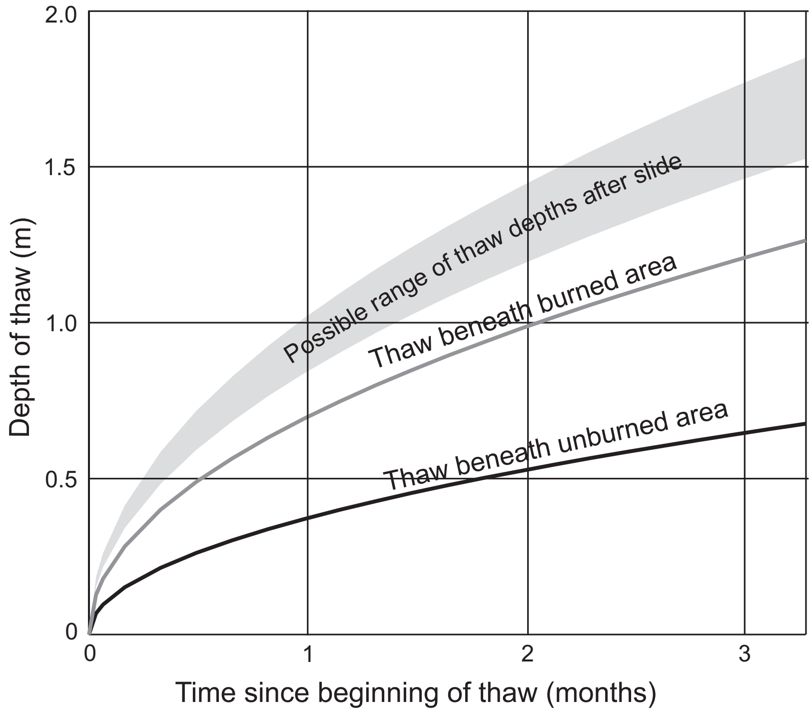

Figure 11.

Progress of frost table deepening under different ground-surface conditions for the Thunder River area. The curves are calculated using the average ground-surface temperature acting over the thawing interval for the burned and unburned site records shown in Figure 10. Burning of the ground cover doubles the active-layer thickness during the first thaw season. If an active-layer detachment occurs, an even deeper thaw is produced, assuming that the air temperature is an accurate estimate of the ground-surface temperature.

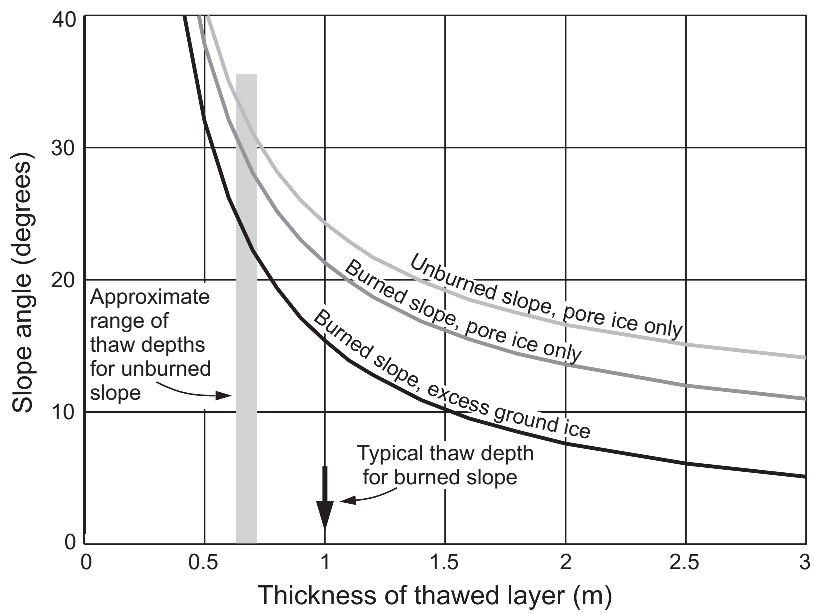

Figure 12.

Slope angles for which the factor of safety for an active-layer detachment = 1, depending on the depth of thaw and the amount of ground ice. The least stable slopes are burned slopes with ground ice in excess of that filling sediment pore space. Increases in average annual air temperature given by general circulation models alone will not have a pronounced affect on slope stability for this type of slide; however, the strong association with slope burning suggests that active-layer slides will become more common if climate change results in an increased incidence of forest fires.

entire thawed soil weight. Therefore, one assumption is that the frictional strength is zero (or $\phi = 0$). If ice in the soil is present only in the pore space, a higher friction will be available but thaw consolidation will still occur and still increase the pore-water pressure. Figure 12 shows examples of the effect of these different soil conditions.

Figure 12 indicates that an active-layer detachment will only form on steep slopes of 30° or more for thaw depths typical of undisturbed terrain in the Thunder River area (maximum thaw depths are 60–70 cm in the Thunder River area (Harry and MacInnes, 1988)). Active-layer detachments on undisturbed terrain in this area are rare, probably because slopes, except river banks, are seldom this steep; however, the maximum slope angle likely to fail decreases markedly as the thaw depth increases. With double the normal thaw depth, a much larger area becomes susceptible to failure because slopes as shallow as 10–15° become unstable. Of course, the likelihood of failure is still uncertain because the amount of ground ice is unknown. Ice characterized by visible lenses is most likely to eliminate friction because melting ice lenses are probably replaced by temporary lenses of water having no shear strength. Ice present only in existing sediment pore space will permit some friction because melting allows sediment particles to come into contact more rapidly. The volume and fabric of ice thus become important in determining stability.

SLOPE STABILITY IN A WARMING CLIMATE

Rotational slides in permafrost will become more likely if climate warming results in decreasing permafrost thickness and hence a decrease in the cohesive strength of sediments forming a slope; however, once a new permafrost thickness is established, slide triggering will revert to such processes as toe erosion. Permafrost thaw may be so gradual that failures due to the corresponding loss of strength may be difficult to distinguish from triggering by active toe erosion. The permafrost thaw may be a factor that simply hastens failure due to other destabilizing processes.

Climate warming may have a more noticeable effect on active-layer detachments; however, the warming must be pronounced for the effect to be noticeable. The gradual warming implied by General Circulation Model predictions amounts to a small fraction of a Celsius degree per year and would require years or decades to produce a marked increase in slide occurrence. Year-to-year variability is likely to be more effective in the short term. For example, the air thawing index averages 1600 degree days at Fort Good Hope but has been as high as about 1900 degree days. Therefore, in any one year, a thawing index considerably greater than the average is possible, resulting in an increase in thaw depth that would only be approached after many years of climate warming at predicted rates. As pointed out already, forest fire is probably the most likely means of triggering an active-layer detachment because of the marked affect on the transfer of heat into the ground. If climate warming is characterized by conditions which become more favourable for forest fire occurrence, then the frequency of active-layer detachments may increase. This may be the most pronounced influence of climate change on slope stability.

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