The transient layer and slope stability in fine-grained permafrost soils

Baolin Wang, Haoqiang Li & Bhuwani Paudel
Natural Resources Canada, Ottawa, Ontario, Canada

ABSTRACT
Permafrost is traditionally defined as ground having temperature at or below 0ºC for at least two consecutive years. This has led to a traditional concept of a two-layer system – active layer and permafrost when ground conditions in permafrost regions are described. Such traditional definition has been recognized to be inadequate for understanding permafrost behaviour. This is especially true for the purpose of slope stability studies. A transient layer between the active layer and the "long-term" permafrost plays a critical role on slope stability. There have been some research works reported about the transient layer. However, its characteristics and influence on slope stability need to be further investigated. Previous research on permafrost slope stability has paid little attention to the transient layer. This paper discusses about the transient layer from geotechnical/slope stability viewpoint. A field program was conducted at 14 landslide sites in the Mackenzie valley, Canada. The geotechnical characteristics of the transient layer and its influence on slope stability are discussed based on the field and laboratory studies.

RÉSUMÉ
Le pergélisol est traditionnellement défini comme un sol ayant des températures égal à ou en dessous de 0 °C pendant au moins deux années consécutives. Cela a conduit à une conception traditionnelle d'un système à deux couches lors de la description des conditions du sol dans les zones de pergélisol, soit la couche active et le pergélisol. Cette conception a été reconnue comme étant insuffisante pour comprendre le comportement du pergélisol. Cela est particulièrement vrai lors des études de stabilité de talus. En effet, il y a une couche transitoire entre la couche active et le pergélisol à "long terme" qui joue un rôle déterminant sur la stabilité des talus. Il y a quelques travaux de recherche qui ont étés rapportés portant sur la couche transitoire. Cependant, ses caractéristiques et son influence sur la stabilité des talus devraient être étudiés davantage. Les recherches antérieures sur stabilité des talus de pergélisol ont porté peu d'attention sur la couche transitoire. Ce document discute donc la couche transitoire d'un point de vue géotechniques/stabilité des talus. Une étude de terrain a été réalisée à 14 sites de glissement de terrain dans la vallée du Mackenzie, au Canada. Les caractéristiques géotechniques de la couche transitoire et son influence sur la stabilité des talus sont discutées en fonction des études de terrain et des essais en laboratoire.

1 INTRODUCTION

There are numerous landslides in fine-grained permafrost soils in the Mackenzie valley, Northwest Territories, Canada (Aylsworth et al. 2000, Couture & Riopel 2007). These landslides are much affected by permafrost behaviour. Figure 1 shows two typical landslides in this region. These landslides usually start from a small scale slope failure and expand every summer due to melting of ice-rich permafrost that are exposed to the atmosphere. These slides are usually circular in shape with near vertical scarp walls around the perimeter. Extensive geotechnical investigations were carried out recently at the Geological Survey of Canada to understand the failure mechanism and triggers of the landslides (Wang et al. 2005, Su et al. 2006, Wang & Saad 2007, and Wang & Lesage 2007). For better understanding the failure mechanism and triggers of such landslides, it is important to identify the geotechnical characteristics of the permafrost soils.

Figure 1. Typical landslides in fine-grained permafrost soils in the Mackenzie valley, Canada

Permafrost is traditionally defined as ground having temperature at or below 0 ºC for at least two consecutive years. Permafrost soil is therefore commonly described with a two-layer system: (1) an active layer that stays frozen for less than two consecutive years, and (2) permafrost that stays frozen for two consecutive years or longer. Due to annual climate fluctuations and other environmental factors, there exists a transition zone that thaws occasionally although it stays frozen for longer than two years most of the time. Wang et al. (2005) indicated that "sudden thawing of this layer may not necessarily cause serious threat to slope stability as, in theory, it has in the recent history undergone at least one cycle of thawing without resulting in slope failure." Despite such reasoning, understanding the characteristics of this layer is of critical importance as it provides insight to understanding how slopes perform when such extreme conditions occur. Reviewing some earlier works, Shur et al (2005) indicated that "despite the importance of this layer, it has been the focus of only a few works." They described the transition zone as two parts. The lower part is ice-rich and thaws at sub-decadal to centennial intervals. The upper part contains less ice content and thaws more frequently. They named the upper part of this transition zone as the transient layer and focused their discussions on this upper most layer. Bockheim and Hinkel (2005) were able to detect the lower boundary of the transition zone for many cases. They indicated that the transition zone generally has a greater amount of segregated ice and moisture content than that of the active layer, a greater amount of organic matter than the near-surface permafrost, and a bulk density intermediate between those of the active layer and the permafrost. Both Shur et al (2005) and Bockheim and Hinkel (2005) referred to the transition zone as one that is subject to episodic thaw at sub-decadal to multi-centennial scales. Its lower bound was considered as the long-term permafrost table that coincides with the top of primary ice wedges, which was conceptualized following Lewkowicz (1994). However, as discussed later in this paper, this may not always be the case. Nevertheless, the current paper points out that the characteristics and the behaviour of the entire transition zone, especially the lower ice-rich part, are critical to understanding stability of permafrost slopes in fine-grained soils. Regardless how infrequently this lower part thaws, it can be detrimental, if it happens, to slope stability due to its high ice content. The focus of this paper is on the entire transition zone including the lower ice-rich part. For this purpose, the entire transition zone is regarded as a transient layer as illustrated in Figure 2. As shown in Figure 2, there are two points A and B. The layer above point A thaws annually and that below point B remains frozen "forever" in terms of engineering interest. A series of field and laboratory programs have been conducted to better understand the geotechnical characteristics of the transient layer. This paper presents some preliminary findings from these investigation programs.

2 FIELD AND LABORATORY INVESTIGATIONS

A field and laboratory investigation program was carried out to characterize the soil moisture conditions at 14 landslide sites in the Mackenzie valley, Canada in June and September 2007. The locations of the sites are shown in Figure 3 (marked as I1 to I5 for the northern sites, and G1 to G9 for the southern sites).

At each site, soil samples were taken from the head walls of the slides to measure their water contents, Atterberg limits, and gradations. Soil samples were taken at 10 cm intervals from the ground surface to a depth of up to 2.8 m. The height of the head walls usually ranges from a few meters to over 15 m.

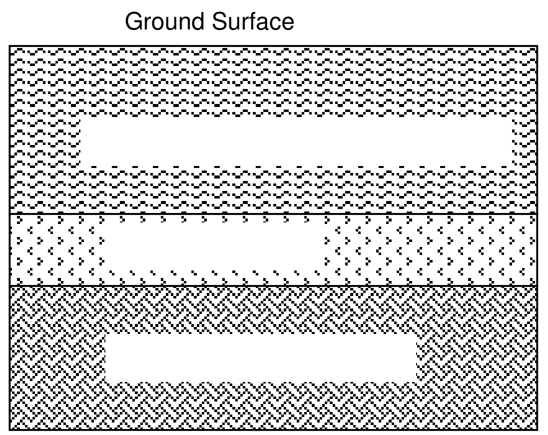


Figure 2. Illustration of a three-layer permafrost ground

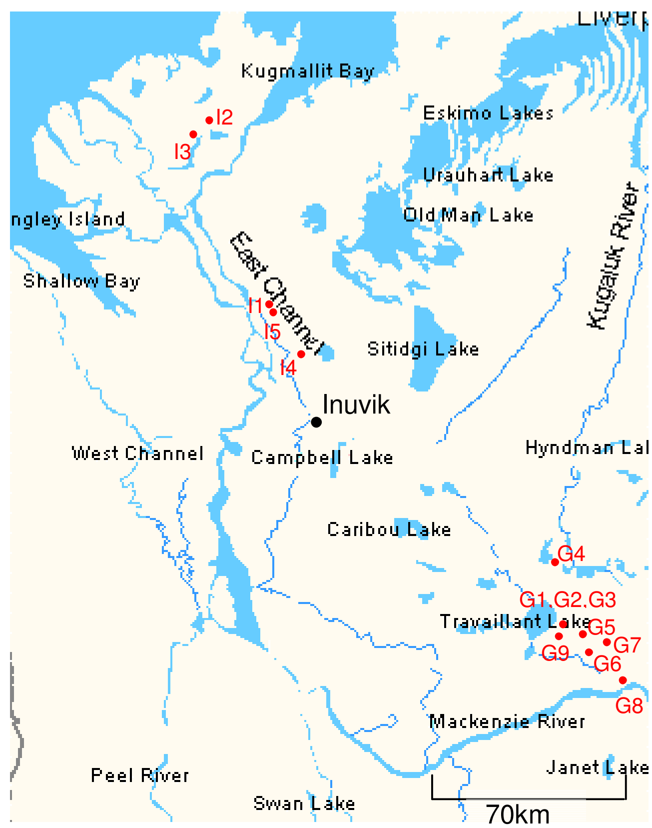


Figure 3. Locations of test sites

The soil samples were taken with an axe and a hand shovel. The active layer was partially frozen at the time when the samples were recovered in June 2007. Loose materials on the wall face were removed before fresh samples were taken. The soil samples were sealed in plastic sample bags and weighed immediately. Soil total water contents, Atterberg limits, and grain sizes were measured at a laboratory of the Geological Survey of Canada.

2.1 Soil Gradation

The subsurface soils observed from the landslide sites are typically silty clay or clayey silt. Typical soil gradation curves are shown in Figure 4. The materials at the southern sites (G-series) are commonly found finer than those of the northern sites (I-series).

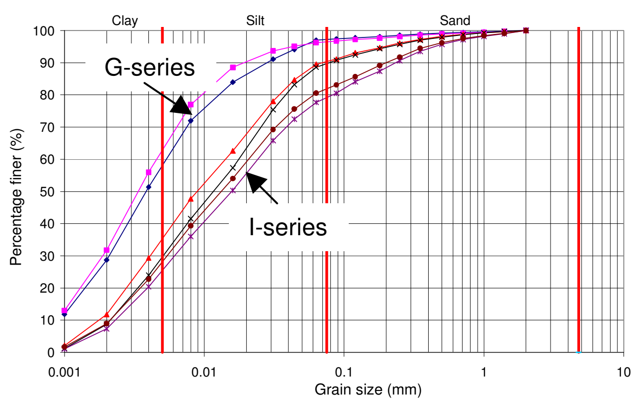


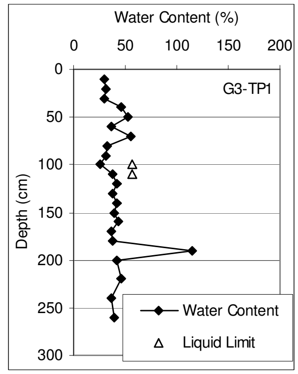
Figure 4. Typical soil gradations

2.2 Soil Total Water Content

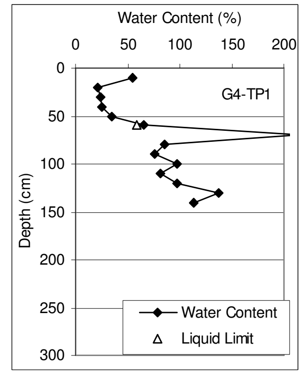
Soil water content data are shown in Figure 5 (where TP denotes Test Pit). The data indicate a range of total water contents from 20% to higher than 100% by weight.

Among the nine landslide sites in the southern area (G1 to G9), two sites (G4 and G8) were covered with mature trees. The other seven sites were burned by relatively recent forest fires in and prior to 1998. No evidence of any recent fire activity was noted at sites G4 and G8, although the sites were probably burned at least once long time ago as some burned signs were occasionally visible. The maximum thaw depth in this region was about 1 m measured in September 2007.

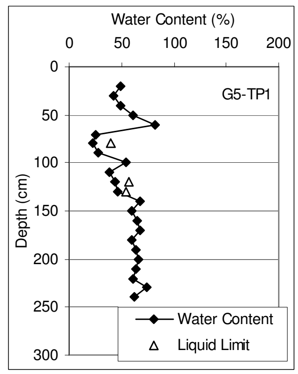
The northern sites (I-series) are located north of the tree line where the surface is covered by typical tundra vegetation of about 15 cm to 30 cm thick. The maximum thaw depth in this region was about 0.5 m measured in September 2007 and other years (Wang et al, 2005, Wang & Saad, 2007).



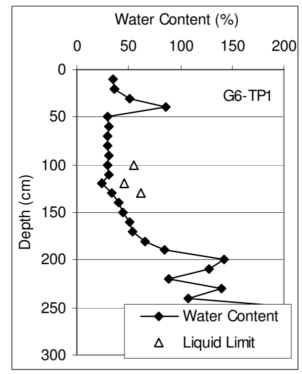
(a) Site G3-TP1



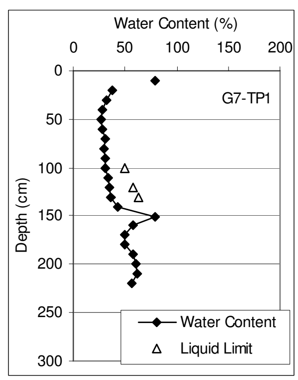
(b) Site G4-TP1



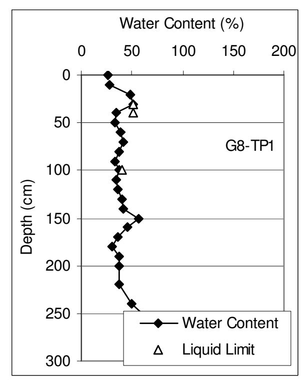
(c) Site G5-TP1



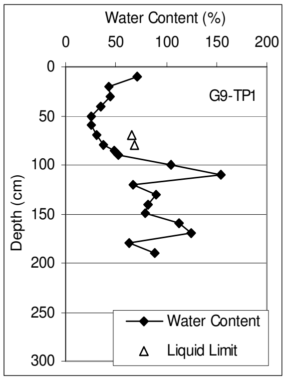
(d) Site G6-TP1



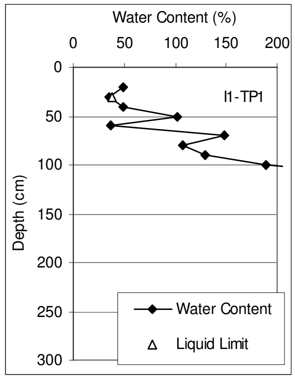
(e) Site G7-TP1



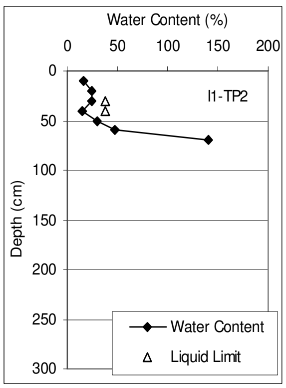
(f) Site G8-TP1



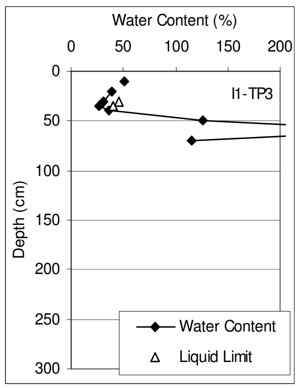
(g) Site G9-TP1



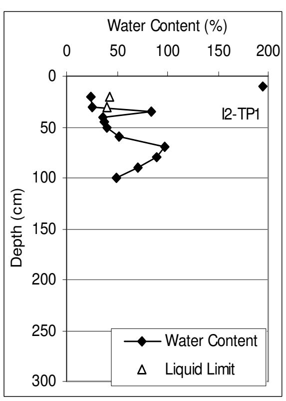
(h) Site I1-TP1



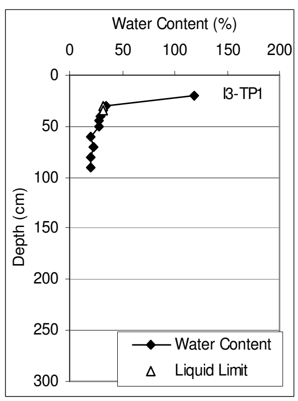
(i) Site I1-TP2



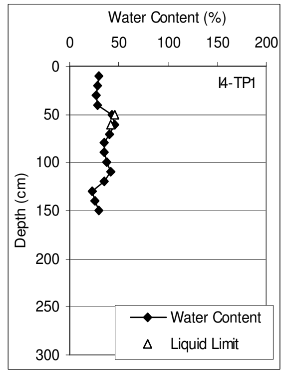
(j) Site I1-TP3



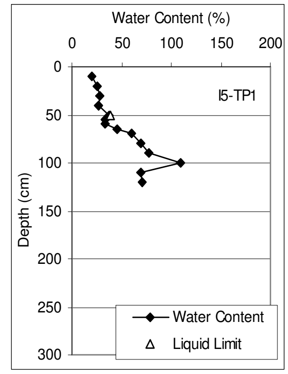
(k) Site I2-TP1



(l) Site I3-TP1



(m) Site I4-TP1



(n) Site I5-TP1

Figure 5. Soil total water content

The charts shown in Figure 5 indicate that the soil total water contents are generally lower in the upper active layer. The occasional high water contents at the top 10 cm depth or so are due to high organic nature of the samples (e.g. Figures 5 e, g and k). The total water contents (as measured when fully thawed) usually increase with depth.

A sharp increase of water content at around 0.5 m to 1 m depth was observed at most test locations as shown in Figure 5. This is consistent with the ice-rich part of the transition zone indicated in Shur et al (2005) and Bockheim and Hinkel (2005).

At some of the southern sites (G-series) another layer with increased water content was also noted at about 1.5 m or greater depth. This indicates that the fire destruction of the surface organic cover perhaps caused deep thaw to about 1.5 m or greater depth for the first few years following the fire. The high water content at the shallower depth of 0.5 m to 1 m is an indication of shallower thaw depth during more recent years when vegetation has partially established.

The I-series sites consistently show significant water content increase at a depth of about 0.5 m. An exception is I3-TP1 where water content decreased. The reason for this is currently unknown, but it could be an isolated case.

2.3 Roots and Other Factors

Root zones were visible along all the landslide head walls investigated. Figure 6 shows a photograph of a typical landslide head wall surface where abundant roots are visible in an ice-rich zone. The root depth can sometimes be an indicator of the maximum depth of thaw that the ground has experienced.

The root depths at several locations along the head wall of landslide I1 were measured to be around 60 cm. Compared with the moisture content data shown in Figures 5 (h), (i) and (j), the root depth coincides with the depth of high moisture concentration at Site I1.

However, root depth alone cannot be used to delineate the lower boundary of the transient layer. This is because roots could have been deposited from previous slumping processes and preserved for a long period of time.

Figure 6. A typical landslide scarp wall showing roots in ice-rich zone

Shur et al (2005) and Bockheim and Hinkel (2005) indicated that the bottom of the "transition zone" coincides with the top of primary ice wedge. While this could be true in most cases, some exceptions were noticed at some landslide sites visited. For example, Figure 7 shows a primary ice wedge in the scarp wall of landslide I1. The top of the ice wedge extended to near ground surface while the maximum thaw depth was typically measured to be about 0.5 m at this site. Obviously, thawing has been extending deeper away from the ice wedge.

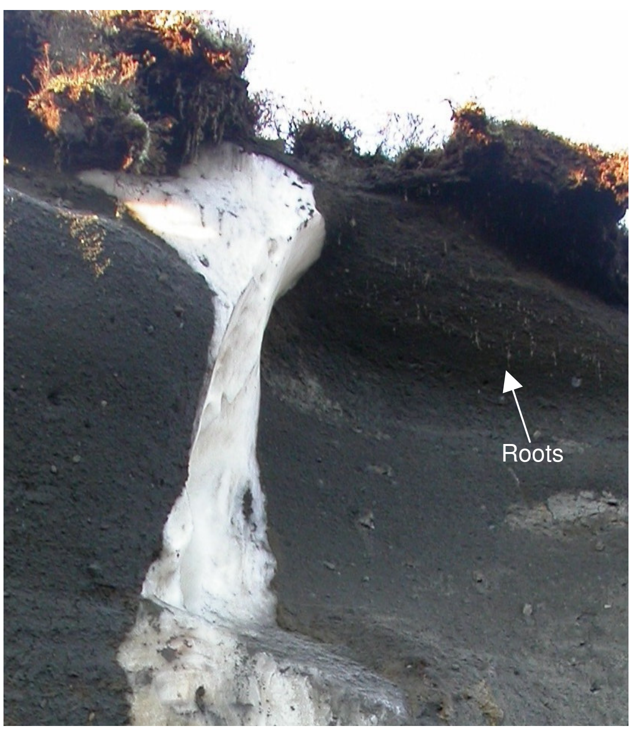


Figure 7. A primary ice wedge extruding to near surface

2.4 Liquid Limits

Liquid limits of the samples collected from some locations are tested and the results are shown in Figure 5. The liquid limits range from 40% to 69% for the southern sites (G-series) and from 35% to 45% for the northern sites (I-series). As can be observed from Figure 5, water contents below the lower part of the transient layer are either close to or higher than the liquid limits. This means that once the ice-rich layer thaws, its shear strength would be very low. If the generated pore water cannot dissipate quickly enough, slope failure may follow.

2.5 The Transient Layer and Slope Stability

A test plot was developed on a slope next to landslide I1. The slope angle was about 10º. The tundra vegetation or the organic mat of about 15 cm to 30 cm thick was removed in an area of 20 m x 20 m to investigate its thermal impact and ground condition changes. Thermisters, inclinometers and other instruments were installed inside and outside the test plot. Details about the test plot are given by Wang and Saad (2007), in which some initial data collected from the test plot during the first year in 2006 were reported. The thaw depths inside and outside the test plot were presented along with slope deformation data. The thaw depths were further measured in September 2007. The new results combined with the 2006 results are presented in Figure 8.

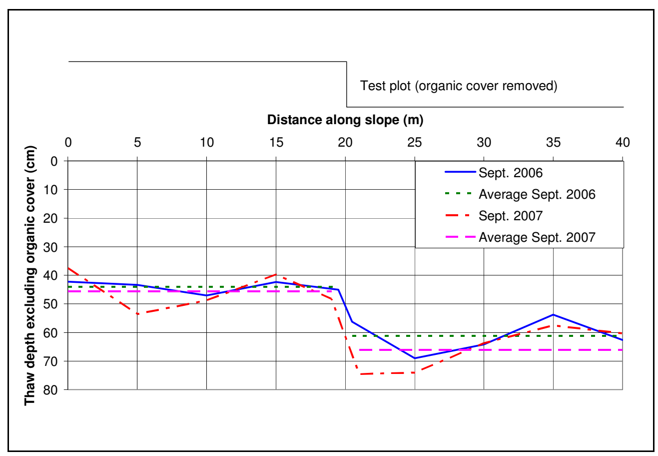


Figure 8. Thaw depth measured at test plot site

As shown in Figure 8, the average thaw depth was 66 cm in the test plot and 46 cm in the undisturbed area measured in September 2007 (the second summer after the test plot was developed). The removal of the organic layer has caused a thaw depth increase by 20 cm during the second summer since the test plot was created. Moreover, the thaw depth in the test plot was about 5 cm deeper during the second year than the first year. Outside the test plot in the undisturbed area, the thaw depth increased by about 2 cm from the first year to the second year.

Comparing Figure 8 with Figures 5 (h), (i), and (j), the thaw depth in the undisturbed area outside of the test plot reached the top of the ice-rich zone of the transient layer; whereas the thaw depth inside the test plot penetrated through the bottom ice-rich zone of the transient layer into the “long-term” permafrost.

The inclinometer inside the test plot measured a 16 mm displacement by the end of the first summer after the test plot was developed. The slope movement was obviously related to the thawing of the ice-rich transient layer mentioned earlier. However, the magnitude of the displacement was limited during the first year. This is probably because of the boundary constraint around the test plot perimeter. This may also be due to the slow thawing process owing to (1) latent heat effect of the increased ice content; (2) lower thermal gradient at depth relative to the surface area; (3) air cooling at the end of summer when thaw depth reached its maximum. The slower thawing process may provide an opportunity for the excess pore water to dissipate. Thawing at the critical depth may also be “short lived” as thawing reaches its maximum depth at the end of summer. Ground freezes back before a significant displacement takes place.

3 CONCLUSIONS

Moisture data collected from 14 landslide sites indicated that moisture contents increase with depth. A transient layer between the active layer and the long-term permafrost is evident at most sites investigated. The bottom of the transient layer usually has increased ice content. Roots are often visible in high ice content zones. Root depth can sometimes be an indicator of the bottom boundary of the transient layer. However, it may not always be the case.

Total water content around the lower part of the transient layer is usually close to or higher than the soil liquid limit. Thawing of this layer may result in significant reduction of shear strength and hence slope failure. If the slope movement is significant enough to expose the underlying permafrost, continued thaw flow may start. However, if thermal factors causing such thawing are limited to severe weather conditions, the slopes should have a good chance to remain stable. This is because of the slow process of slope movement and short duration of the deep thaw period.

ACKNOWLEDGEMENTS

The authors wish to thank Dr. Sharon Smith and Dr. Réjean Couture for their critical review and comments.

ESS Contribution number: 20070258

REFERENCES

Aylsworth, J.M., Duk-Rodkin, A., Robertson, T. & Traynor, J.A. 2000. Landslides of the Mackenzie valley and adjacent mountainous and coastal regions. *The Physical Environment of the Mackenzie Valley, Northwest Territories: A Base Line for the Assessment of Environmental Change.* Edited by L.D. Dyke and G.R. Brooks, Geological Survey of Canada, 2000 Bulletin 547:167-176.

Bockheim, J.G. & Hinkel, K.M. 2005. Characteristics and significance of the transition zone in drained Thaw-Lake Basins of the Arctic Coastal Plain, Alaska. *ARCTIC.* 58(4): 406-417.

Couture, R. & Riopel S., 2007. Regional landslide studies in the Mackenzie valley, Northwest Territories, Canada: results from photo-interpretation and susceptibility mapping. *Proceedings, 1st North American Landslide Conference*, June 2007, Vail, Colorado: 1552-1561.

Lewkowicz, A.G. 1994. Icewedge rejuvenation, Fosheim Peninsula, Ellesmere Island, Canada. *Permafrost and Periglacial Processes*, Vol. 5. pp.251-268.

Shur, Y., Hinkel K.M. & Nelson, F.E. 2005. The transient layer: Implications for geocryology and climate-change science. *Permafrost and Periglaial Processes*, 16: 5-17.

Su, X., Wang, B. & Nichol, S. 2006. Back analysis of a slope failure in permafrost in the Mackenzie valley, Canada. *Proceedings of the 13th International Conference on Cold Regions Engineering*. Orono, Maine.

Wang, B., Nichol S. & Su, X. 2005. Geotechnical field observations of landslides in fine-grained permafrost soils in the Mackenzie Valley, Canada. *Proceedings of the First General Assembly of the International Consortium on Landslides*, edited by K. Sassa, H. Fukuoka, F. Wang & G. Wang (Eds.) 13-14 October 2005, Washington, D.C., Chapter 25, 203-212.

Wang, B. & Saad, B. 2007. In-situ measurements of ground response to heat penetration induced by removal of organic cover in fine-grained permafrost soils. *Proceedings of the 1st North American Landslide Conference*, June 3-8, 2007, Vail, Colorado, 1595-1604.

Wang B. & Lesage K. 2007. Impact of climate change on slope stability in permafrost region. *Proceedings, 8th International Symposium on Cold Region Development*, Tampere, Finland, Sept. 2007.