

Landslides (2009) 6:121–127
 DOI 10.1007/s10346-009-0150-y
 Received: 1 May 2008
 Accepted: 12 March 2009
 Published online: 23 April 2009
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Retrogression characteristics of landslides in fine-grained permafrost soils, Mackenzie Valley, Canada

Abstract Thirteen landslides (retrogressive thaw flows) were investigated to study the behavior of thaw retrogression in permafrost in the Mackenzie Valley, Northwest Territories (NWT), Canada. Those landslides are all in fine-grained ice-rich permafrost soils. Such landslides usually start from small-scale slope failures followed by retrogressive thaw flows when ice-rich permafrost soils are exposed to the atmosphere. The landslides were marked with survey stakes to measure their retreat rates for the thawing season of 2007. Two correlations are presented: one is between scarp wall height and retreat rate; another is between overall slope angle and retreat rate. It was found that thaw flow retrogression rate increases with increase in scarp wall height and slope angle up to a certain limit. It was also confirmed that thaw flow retrogression is not influenced by slope orientation.

Keywords Landslide · Thaw flow · Permafrost · Retrogression · Slope orientation · Canada · Mackenzie Valley

Introduction

Retrogressive thaw flows are slope failures in fine-grained permafrost soils resulting from thawing of ice-rich permafrost (Everdingen 2002). Fine-grained permafrost soils are commonly ice-rich and behave like a “slurry” after thawing (McRoberts and Morgenstern 1974; Wang et al. 2005). A small-scale failure exposes ice-rich permafrost to the atmosphere. Retrogressive thaw flow starts due to continued thawing of exposed ice-rich materials. The debris flows away, usually to a lake downstream. Such thaw flows may start from a small-scale slope failure that can be as small as a few meters diameter and retrogress over a distance as large as a few hundred meters. Figure 1 shows a typical retrogressive thaw flow in the Mackenzie Valley, Northwest Territories (NWT), Canada. Retrogressive thaw flows consist of a near vertical headwall that retreats every summer. The debris consists of thawed sediments and melted water that can flow at an angle as low as 1° to 2°. Such retrogressive failures may remain active for years as long as the ice-rich materials are exposed. They may impose serious impact on infrastructures, e.g., highways or pipelines (Ma et al. 2006). Understanding the failure processes and documenting the rate at which these failures retrogress are important for developing appropriate remedial measures.

Several researchers have discussed the behavior of retrogressive thaw flows (also called thaw slumps or mudflows). Lamothe and St-Onge (1961) reported that the retreat rates of a thaw flow in Ellef Ringes Island, NWT averaged about 7 m, with a maximum of 10 m in a summer season. McRoberts and Morgenstern (1974) investigated ablation problems of different thaw flows along the Mackenzie Valley, NWT. They reported that ablation rate was 1 to 20 cm/day with an average of 10 cm/day. Burn and Friele (1989) studied three retrogressive thaw flows near

Mayo, Yukon Territory, Canada. The short-term mean retreat rates of two sites were reported to be 7.4 and 11.1 cm/day from June 30 to July 9, 1982, respectively. The mean (year 1949 to 1987 and 1961 to 1987) annual headwall retreat rates were measured to be approximately 12 and 14 m, respectively, for two sites. Burn and Lewkowicz (1990) reported the head-scarp ablation continued at a rate of 14 to 16 m/year for many years at Stewart River near Mayo. Burn (2000) reported that ablation rate of a retrogressive thaw flow near Mayo was as high as 16 m/year, with an average ablation rate of 10 m/year.

It has been somewhat controversial about the influence of slope orientation on retrogressive thaw flows. Kerfoot (1969) observed slope failures on Garry Island (NWT, Canada) and indicated that the movement of headwalls did not have preference on south facing or north facing slopes. Aylsworth et al. (2000) indicated that landslide inception showed no particular preferred orientation in a survey of 3,400 landslides in the Mackenzie Valley region. McRoberts and Morgenstern (1974) indicated that the lack of orientation preference may have been due to the 24-h daylight during the summer months. However, Lewkowicz (1988), who studied short-term rates of ablation of massive ground ice in Mackenzie Delta, NWT, reported that ice face orientation affected the timing and total amount of ablation during clear skies but was insignificant during overcast conditions.

Pufahl and Morgenstern (1980) discussed the behaviors of retrogressive thaw flows based on energy-balance calculations. The observed average rate of ablation for a north facing large landslide, near Fort Simpson, NWT, was 14 cm/day from June 21 to July 21, 1974. It was concluded that there was no correlation between retreat rates and insolation. There was no reduction in retreat rates for the slopes facing north.

Due to controversy and limited data reported from the literature, a site investigation program was carried out in 2007 to further study the behavior of retrogressive thaw flows. A total of 15 locations at 13 landslide sites in the Mackenzie Valley were monitored. The retreat rates of the scarp walls were measured. Soil samples were taken from the scarp walls for geotechnical index testing. Landslide size, slope angle, and main scarp orientation were also measured. This paper presents the results of these studies.

Site conditions and the field investigation program

Wang et al. (2005) reported a total of 97 active landslides observed during a flight along a 750-km long and approximate 20-km wide corridor in the northern half of the Mackenzie Valley, Canada, in 2005. Most of those landslides were retrogressive thaw flows and located in the northern part of the corridor. A majority of the landslides were around lakes in gently rolling terrain of hummocky, ice-rich glaciolacustrine sediments.



Fig. 1 A typical retrogressive thaw flow in tundra region. The area affected was about 10,000 m² or approximately 100 m diameter by 2007 and is still expanding (I4 corresponds to the landslide site location on Fig. 2)

Among those landslides, 13 sites were selected for this study in 2007. The locations of the sites are shown in Fig. 2. All of the landslides selected were around lakes. Four sites were in tundra area, north of Inuvik, and nine were in forest area, south of Inuvik.

The northern sites are in Inuvialuit Settlement Region and are depicted as I1 to I5. The southern sites are in Gwich'in Settlement Region and are depicted as G1 to G9.

Surface vegetations in the two study regions are drastically different. The northern sites (I1 to I5) are covered by typical tundra vegetation with little or no trees (see Fig. 1 as an example). The ground in this region is covered by a layer of organic mat of about 15 to 30 cm thick (locally thinner or thicker) that consists of roots or moss. The subsurface materials exposed in the landslide scarps are clayey silt or silty clay with trace sand and gravel and occasional cobbles (glacial till deposit). The active layer is about 0.5 m thick underlain by ice-rich permafrost.

The southern sites are in forested areas. Most of the landslides selected are in burned areas where trees and vegetation were destroyed by relatively recent forest fires that occurred in or before 1998. Figure 3 shows a typical site with three landslides (G1, G2, and G3) in a burned area, where G1 started earlier than G2 (exact starting time unknown), and G3 started in 2004 and joined G1 in 2006. Sites G5, G6, G7, and G9 are in a recently burned area while sites G4 and G8 (Fig. 4) are in forested areas with no sign of any recent fire activity. The subsurface materials observed from the landslide scarps are mostly silty clay. The active layer is about 1 m thick in the burned areas and thinner in the unburned area where mature trees and vegetation provided insulation to the subsurface

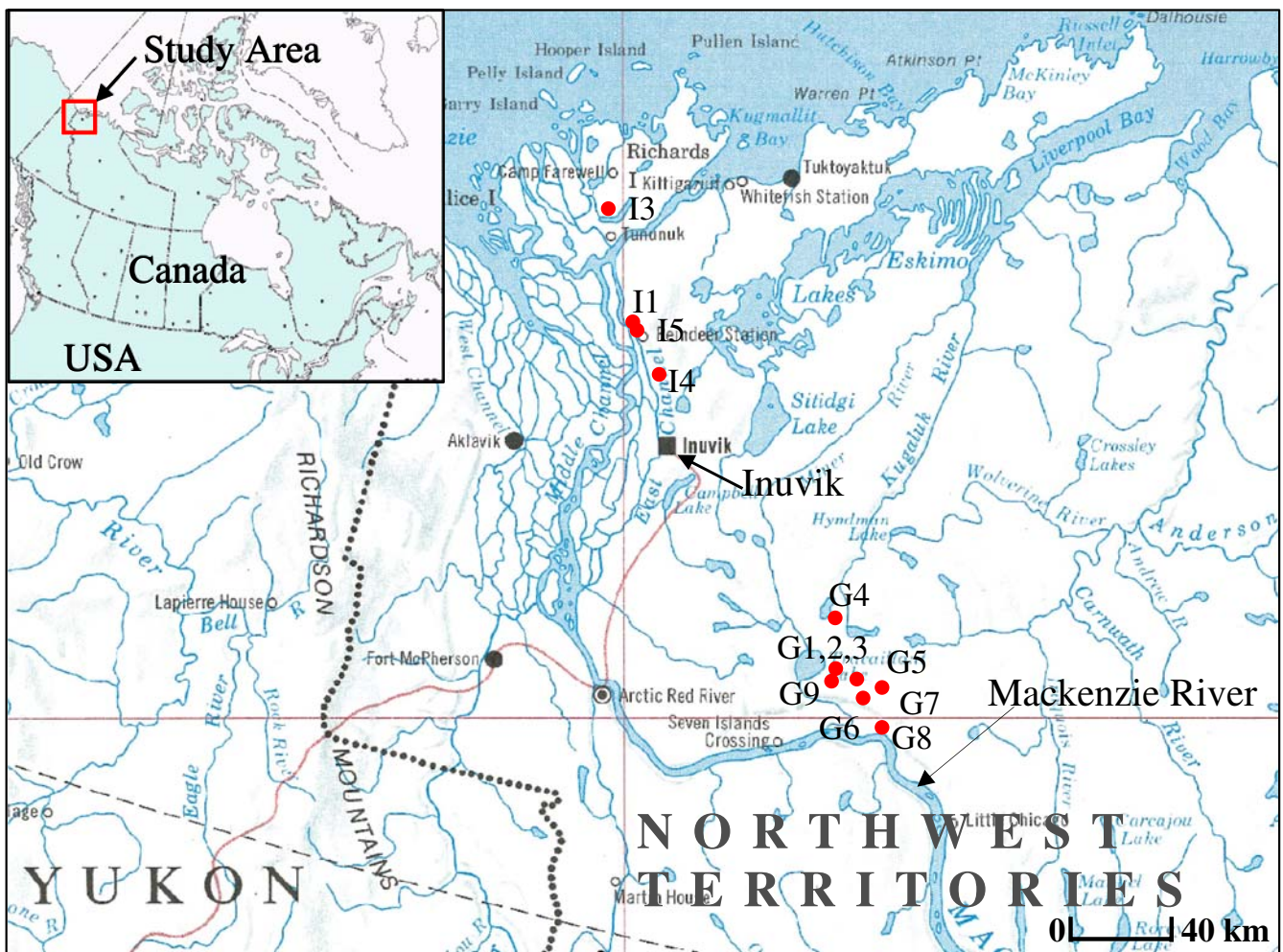


Fig. 2 Site location map (dots with notation I1 to I5 and G1 to G9 indicate study site locations)



Fig. 3 Typical landslides in burned forest area (G1 started a few years before 2004, exact time unknown; G2 likely started after G1; and G3 started in 2004; G1 and G3 merged together in 2006. A survey stake G1-STK3/G2-STK1 for measuring G1 and G2 retrogression distances was installed at the narrow strip between G1 and G2). The maximum width of G1 was about 150 m in 2007

soils. The sites are located in continuous permafrost region, where permafrost extends to a great depth (in the order of hundred meters according to Taylor et al. 2000, and Smith and Burgess 2002). The fine-grained permafrost soils are usually ice-rich.

A field investigation program was conducted in 2007 and 2008 with two trips to the sites in 2007 and a follow-up trip in 2008. The first trip in 2007 was from June 14 to 21, right after the spring breakup. The second trip was at the end of the summer from September 6 to 14, 2007 and the follow-up trip was from March 19 to 20, 2008.

Weather data recorded in Inuvik, NWT, from 1958 to 2008 were obtained from Environment (2009). The minimum and maximum Mean Annual Air Temperatures (MAAT) and air thawing indices (I_{at}) are provided in Table 1. Also presented in Table 1 are the



Fig. 4 A typical landslide (G8) in forested region with an area of about 30,000 m² (maximum width about 190 m) by 2007. A small landslide initiated next to the large one

Table 1 Historical mean annual air temperatures (MAAT) and air thawing indices (I_{at}) in Inuvik, NWT, Canada (1958–2008)

Description	MAAT (°C)	I_{at} (°C·day)
Minimum	−11.8	939
Maximum	−4.5	1,822
Average	−8.8	1,309
2007	−7.6	1,376

MAAT and I_{at} for the study year 2007. As noted from this table, the weather in the region in 2007 was around the normal condition.

The ground surface was still covered by snow at the end of May 2007 when an attempt was made for the first field trip. Snow patches were still visible in some shaded areas, and lakes were partially frozen during the June 2007 field visit. During the first field visit, survey stakes were installed at 20 and 40 m upslope from the crest of each landslide visited. Based on the snow coverage and lake ice conditions observed, it is believed that the summer retrogression of the landslides just started at the time of the June visit. This was also evident from some other survey stakes installed previously for other studies as part of this project. Most of the sites were surveyed again during the subsequent September visit. Some of them were not surveyed in September 2007 due to unfavorable weather conditions for site access by air. However, some of the sites missed in 2007 were investigated in March 2008 when the ground was still fully covered by snow. As indicated in Wang and Lesage (2007), the ground in the Northern Mackenzie Valley region starts to freeze in late September under normal conditions. It is, therefore, believed that the two (spring and fall) measurements represented about the whole year's retrogression of the landslides for the year 2007.

More than 280 soil samples were taken from the landslide sites during the field visits, mainly for soil water content measurements for a separate study. Most of the samples were taken from the headwalls of the landslides. Representative locations were selected for sampling to get a continuous profile of soil moistures from the ground surface to a maximum depth of 2.8 m. The maximum sampling depth at each site was determined so that the samples were well below the permafrost table. The moisture samples of around 200 g each were taken with hand tools at 10 cm intervals at each location. Some other samples were taken for soil grain size and Atterberg limits analysis.

Landslide size, slope angle, scarp height, and orientation were also measured using a TruPulse 200 laser range finder, measuring tape, and magnetic compass during the field visits.

Geotechnical index properties

Figure 5 shows the grain size data of the soil samples taken from seven test locations. The materials are mostly silty clay or clayey silt. The samples from the southern sites (G series) contain more fines than those from the northern sites (I series).

The total water contents (including pore ice melt) of the soil samples were measured in a laboratory at the Geological Survey of Canada, Ottawa. Two typical soil moisture profiles for the northern and southern sites are shown in Fig. 6. The results indicate that the total water contents increase with depth ranging from about 20% in the active layer to greater than 100% below the permafrost table. The fine-grained soils are usually ice-rich in permafrost below about 0.5 m depth at the northern sites and about 1.0 m depth at the southern sites.

Fig. 5 Typical grain size distribution of soils from the test sites

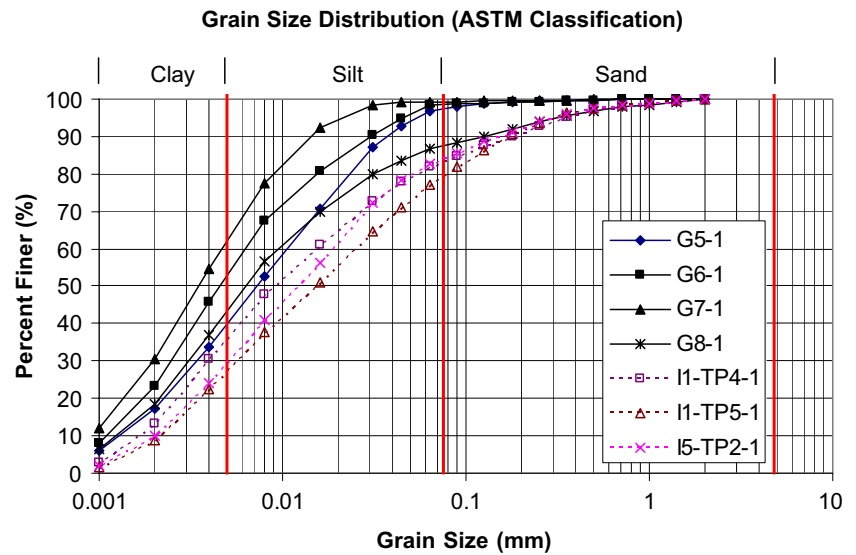


Fig. 6 a, b Typical soil moisture profiles

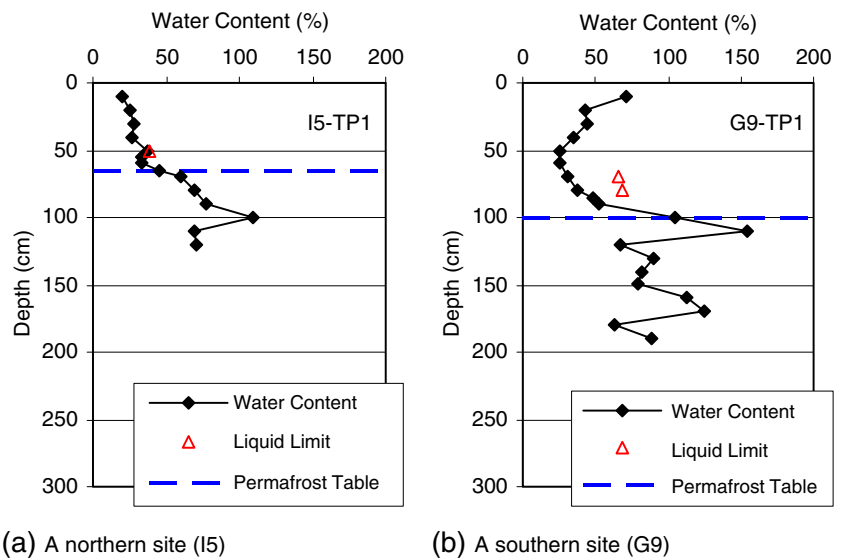


Table 2 Landslide scarp dimension and retrogression during summer 2007

Site location	Length of landslide ^a (m)	Width of landslide ^a (m)	Height of wall (m)	Overall slope angle (°)	Scarp wall dipping direction	Scarp retrogression (m)
I1-STK1	114	133	9.1	10.9	N50°E	7.0
I3-STK1	8	12	2.5	–	N0°E	1.8
I4-STK1	89	130	13.0	9.7	N80°E	8.0
I5-STK1	39	56	6.6	12.1	N100°E	5.6
G1-TP2	130	147	5.0	8.0	N17°W	6.7
G1-STK2	130	147	7.0	8.0	N107°W	9.3
G1-STK3	130	147	6.0	8.0	N180°E	9.0
G2-STK1	110	147	5.8	9.1	N0°E	9.0
G3-STK1	37	60	4.0	9.1	N119°W	6.5
G4-STK2	164	218	15.0	6.0	N30°E	8.8
G5-STK2	138	95	8.2	7.0	N70°W	7.0
G6-STK2	125	115	6.4	6.0	N18°E	6.5
G7-STK2	120	102	2.2	4.0	N56°E	4.7
G8-STK2	195	192	14.5	9.0	N0°E	9.7
G9-STK2	178	138	7.0	4.8	N170°W	7.6

^a Length of landslide was measured as the largest dimension from crest to outlet of debris flow; width was measured as the largest dimension perpendicular to landslide direction

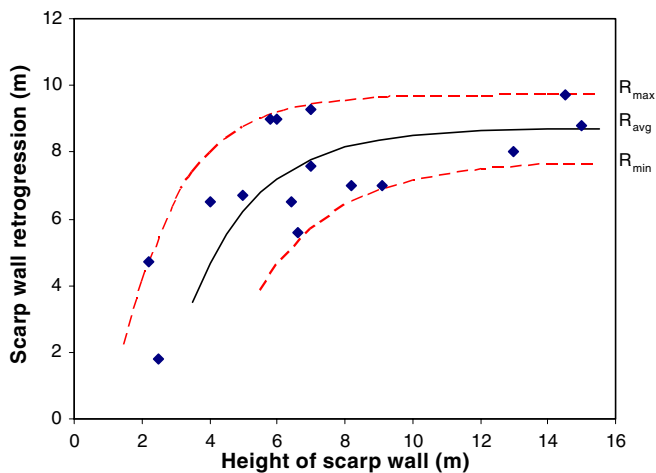


Fig. 7 Relationship between landslide head scarp retreat rate and height of scarp

Liquid limits measured for some samples are shown in Fig. 6. The soils above and below the permafrost table are usually observed as the same type of materials. However, the total moisture contents in the permafrost zone are usually greater than the liquid limit. This is almost always evident by high ice content in the permafrost zone. As mentioned earlier, once such soil exposes to the atmosphere and thaws, it behaves like a “slurry” and flows easily.

Rate of headwall retrogression

Distance between the head scarps and the survey stakes installed in June 2007 at each landslide site were measured in September 2007 and March 2008. The landslide geometrical and retrogression data for the summer of 2007 are summarized in Table 2.

The measured values of the landslide retrogression rates ranged from 4.7 to 9.7 m during the thaw season of 2007.

The retrogression rates are compared with the heights of the scarp walls in Fig. 7. Despite data scattering, the chart indicates an approximate correlation between the rate of scarp retreat and the height of the scarp wall. An upper bound and a lower bound of the data along with an average trend line are delineated on the chart. All the three curves can be expressed by the following equation:

$$R = a - b \times e^{(-H/c)} \quad (1)$$

where R denotes rate of scarp wall retrogression per summer (in meter); H is height of scarp wall (in meter); and a , b , and c are fitting constants with values listed in Table 3.

The scarp wall retrogressions were compared with slope angles in Fig. 8. The slope angles were measured from the crests of the headwalls to the exit points of the debris flow all at the lake shore.

Table 3 Constant parameters for scarp wall height-retrogression correlation (Eq. 1.)

Constant	Lower curve	Average	Upper curve
A	7.7	8.7	9.7
B	42.0	30.0	18.0
C	2.3	2.0	1.7

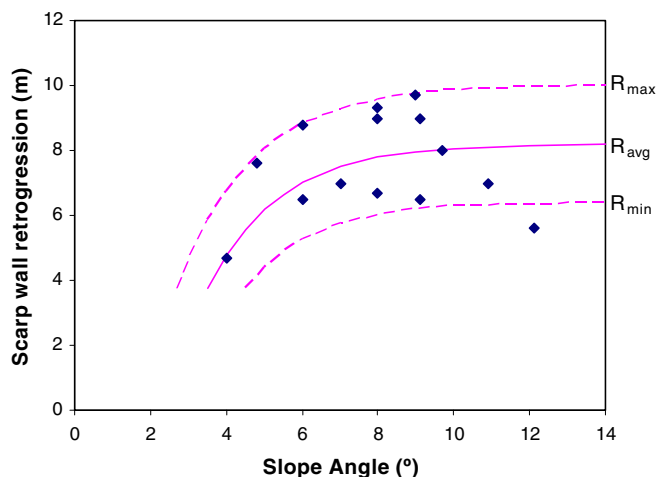


Fig. 8 Rate of retrogression vs. overall slope angle

It is found that an equation identical to Eq. 1. can be used to model the retreat rate and slope angle:

$$R = a' - b' \times e^{(-\alpha/c')} \quad (2)$$

where R denotes scarp wall retreat rate per summer (in meter); α denotes overall slope angle (in degree); and a' , b' , and c' are constants with values listed in Table 4.

It should be noted that the correlations given by Eqs. 1 and 2 represent the data from one summer of 2007, which was close to the normal weather condition as discussed earlier. Depending on the weather condition, the rate of scarp wall retrogression may vary. Therefore, the correlations provided here are general guidance for estimating the rate of retrogression.

As discussed earlier, thaw flow process continues as long as ice-rich permafrost is exposed to the atmosphere. The failures with lower scarp walls retreated more slowly because in most of these cases, the scarps were covered or partially covered by the materials fallen off the scarp wall. The materials from the active layer have lower water content compared to those from the permafrost where soil contains high water/ice content. The ice-rich soil behaves like a “slurry” when melted and flows away relatively quickly from the scarp (Wang et al. 2005). When such “slurry” is mixed with the upper active layer materials, its fluidity decreases, resulting in a decreased flow rate of the debris. This causes the debris to aggrade at the toe of the scarp and to cover part of the ice-rich permafrost wall. The reduced exposure of the ice-rich permafrost results in decreased amount of “slurry” being released from the melting scarp. As the debris builds up at the toe of the scarp wall, its weight increases as well. When the buildup is high enough, the mass slides away driven by its own weight. Thus, the covered ice-rich permafrost along the scarp wall is

Table 4 Constant parameters for slope angle-retrogression correlation (Eq. 2)

Parameter	Lower curve	Average	Upper curve
a'	10.0	8.2	6.4
b'	24.0	28.0	32.0
c'	2.0	1.9	1.8

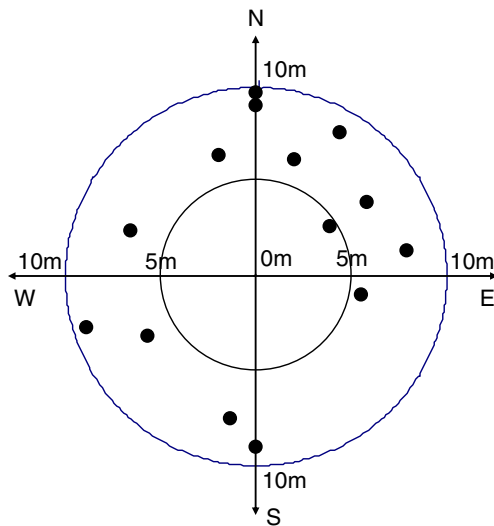


Fig. 9 Relationship between scarp wall retrogression and orientation

re-exposed, and melting is accelerated until it is covered again. The cycle repeats throughout the summer.

The retrogression rate is higher for failures with higher scarp walls. This is because: (a) the accumulating debris cannot build up high enough at the base of the scarp to block the ice-rich permafrost from melting; (b) the materials falling off the scarp wall may have higher water content and, therefore, can flow more easily. This can be due to a higher ratio of ice-rich permafrost to active layer (about 0.5 to 1 m thick in the study region) materials in the mixed mass. This process explains that once the scarp wall reaches a certain height, ablation is at its full potential throughout the summer and a maximum retrogression occurs. Figures 7 and 8 indicate that maximum retrogression may occur for scarp walls higher than 6 to 8 m or overall slope angle greater than about 8° from horizontal.

Although there is a reasonable correlation between slope angle and retrogression rate, the correlation between scarp wall height and retrogression rate is probably more meaningful. This is because the scarp wall height determines how much permafrost is exposed.

Retrogression and slope orientation

The dipping directions of the scarp walls where retrogression rates were measured are also shown in Table 2. The retrogression rates are plotted against the scarp orientations as shown in Fig. 9.

Most displacements were measured at the highest scarp wall, usually at the highest ground elevation along the footprint of the slope failure. Some of them were at the side or lateral scarp walls, e.g., G1-TP2 and G1-STK3 in Table 2.

It should be noted that landslides G1 and G2 are next to each other flowing to two different lakes (Fig. 3). G1 faces southwest and G2 faces north. A survey stake marked as G1-STK3 and G2-STK1 was installed between landslides G1 and G2 to measure the retreats of both scarp walls facing exactly the opposite directions (the G1 wall faced south and G2 wall faced north at retreat points monitored). The measurements indicated exactly 9 m of retreat for both scarp walls. Given the close vicinity of the two measured walls, hence, the identical geotechnical and environmental conditions (other than facing orientation), these data are a strong indication

that landslide retrogression rate does not have preference over south facing or north facing.

The landslide orientation plotted in Fig. 9 also shows that thaw flow retrogression does not have any preference over slope orientation. The landslide retrogression rates are fairly evenly distributed in all directions where data are available. Although it happened that more data are available in three quarters, northeast, northwest, and southwest, observations from the field indicate that most of the slope failures are in near circular shape. It means that the scarp walls have been retreating evenly around the failed zone, most of which has a portion of the wall inevitably facing southeast.

Conclusions

Field studies of 13 landslides in fine-grained permafrost soils indicated that there is an approximate correlation between the failure retrogression rate and the height of the scarp wall. The retrogression rate increases with increase in scarp wall height. The scarp wall may retreat as far as 10 m/year. Retrogression rate does not increase further with the height of the scarp wall exceeding about 6 to 8 m. A similar correlation was also found between failure retrogression and overall slope angle. However, the correlation with the scarp wall height might be more reasonable.

Convincing evidences have shown that thaw flow process does not have preference over slope orientation. North facing landslides or scarp walls do not necessarily retreat slower than south facing ones.

It should be noted that the results are based on the data from one thawing season in 2007. It is believed that the results are representative, although some variations are expected with annual weather fluctuations.

Acknowledgement

The authors wish to thank the anonymous reviewers for their valuable comments that have helped improvement of this paper. ESS Contribution number: 20080095

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