MOVEMENT BEHAVIOUR OF THAWFLOWS IN PERMAFROST SOILS

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RÉSUMÉ
Cet article présente les résultats d'une étude portant sur les phénomènes d'instabilité de pente en milieu pergélisolé observés sur des sites de plusieurs glissements de terrain le long de la vallée du Mackenzie, au Canada. Les glissements de terrain dans les sols fins du pergélisol débutent généralement par de petites ruptures qui sont suivies par des écoulements rétrogressifs lorsque les sols riches en glace sont exposés à l'air ambiant. Plusieurs sites affectés par des glissements de terrain le long de la vallée du Mackenzie ont fait l'objet d'une investigation détaillée et d'un suivi instrumental. Les taux d'accroissement des surfaces mobilisées par les glissements de terrain ont été mesurées, et des échantillons de sol ont été prélevés au niveau de la couronne des glissements afin de réaliser des essais géotechniques. Les caractéristiques du phénomène de rétrogression sont présentées en se basant sur les résultats obtenus à partir des données de terrain et des essais de laboratoire. On observe que les glissements de terrain affectant les sols fins pergélisolés ont une rétrogression d'autant plus rapide que la hauteur des escarpements est importante. La vitesse de la rétrogression n'est pas influencée par l'orientation de la pente.

ABSTRACT
This paper presents results of an investigation of slope failure processes at several landslide sites in permafrost in the Mackenzie valley, Canada. Landslides in fine-grained permafrost soils usually start from small-scale slope failures followed by retrogressive thawflow when ice-rich permafrost soils are exposed to the atmosphere. Several landslide sites in the Mackenzie valley were inspected and monitored. The rates of the landslide footprint expansion were measured. The subsurface soils were sampled from the head scarps of the landslides for geotechnical index testing. The characteristics of the landslide retrogression are presented based on the results obtained from field measurements and laboratory testing. It is noted that landslides in fine-grained permafrost soils retrogress faster with higher scarp walls. The retrogression rate is not influenced by slope orientation.

1. INTRODUCTION

Landslides or thawflows in fine-grained permafrost soils commonly start from small-scale slope failures. Fine-grained permafrost soils are usually ice-rich and behave like a “slurry” after thawing (Wang *et al.* 2005). Retrogressive thawflow starts when such soils are exposed to the atmosphere along slopes. Thawing induced ablation takes place continuously along the head scarp. Such thawflows may remain active for years as long as the ice-rich materials are exposed. Thawflows may impose serious impact on infrastructures, e.g., highways or pipelines. Understanding the failure processes is important for developing appropriate remedial measures.

Thawflow movement behaviours were observed by several researchers. Lamothe and St-Onge (1961) reported that the retreat rates of a mudflow 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 thawflows along the Mackenzie Valley. They reported that ablation rate was 1 to 20 cm per day with an average of 10 cm per day. Burn and Friele (1989) studied three retrogressive thaw slumps near Mayo, Yukon Territory. The short-term mean retreat rates of two sites were reported to be 7.4 cm and 11.1 cm per day from June 30 to July 9, 1982 respectively. The mean (year 1949 to 1987 and 1961 to 1987) annual head scarp retreat rates were measured to be approximately 12 m 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 per year for many years at Stewart River near Mayo, Yukon Territory. Burn (2000) reported that ablation rate of a retrogressive thaw slump near Mayo, Yukon Territory, was as high as 16 m per year, with an average ablation rate of 10 m per year.

Reports about the influence of slope orientation on thawflow process have been somewhat controversial. Kerfoot (1969) observed thawflow activity on Garry Island and indicated that the movement of head scarps did not have preference on south facing slope or north facing slope. In other words, slope orientation had little effect on retreat rates of head scarps. 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 this may have been due to the 24 hour daylight during the summer months.

Lewkowicz (1988) studied short-term rates of ablation of massive ground ice in Mackenzie Delta, NWT, Canada. It was reported that ice face orientation affected the timing and total amount of ablation during clear skies, but was insignificant during overcast conditions.

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Pufahl and Morgenstern (1980) presented a study of the behaviors of thawflows based on energy balance calculations. The observed average rate of ablation for a north facing large landslide, near Fort Simpson, NWT, was 14 cm per 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 investigate the thawflow retrogression behaviour. A total of 14 landslide sites in the Mackenzie valley, Northwest Territories, Canada were investigated. The retrogression rates of the head scarps of the slides were measured. Soil samples were taken from the scarp walls of the slides for geotechnical index testing. The geometries of the landslides and the original slopes and their orientation were also measured.

2. SITE DESCRIPTIONS

During a site visit to the Mackenzie valley in the summer of 2005, a total of 97 active landslides were counted along a 750 km long and approximate 20 km wide corridor starting from the Beaufort Sea (Wang *et al.* 2005). Most of those slides were located in the northern part of the corridor. A majority of the slides were around lakes in gently rolling terrain of hummocky till.

The 14 landslide sites selected for this study in 2007 are located in the northern part of the Mackenzie valley. The locations of the sites are shown in Figure 1. The landslide sites were marked with survey stakes between June 14 and 21, 2007. All of the landslides selected were around lakes. Five 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. A typical landslide in this region is shown in Figure 2. The ground in this region was covered by a layer of organic mat of about 5 cm to 30 cm thick (locally thicker) that consists of roots or moss. The subsurface materials observed from the landslide scarps were clayey silt or silty clay with trace sand and gravel and occasional cobles (glacial till deposit). The active layer was about 0.5 m thick underlain by ice-rich permafrost.

The southern sites are in forested areas. Most of the slides selected were in burned areas where trees and vegetation were destroyed by relatively recent forest fires that occurred around 1998. Figure 3 shows a typical site with three slides (G1, G2 and G3) in a burned area, where G3 started in 2004 and joined G1 in 2006. Slides G5, G6 G7 and G9 are in recently burned area while slides G4 and G8 (Figure 4) are in heavily treed areas with no sign of any recent fire activity. The subsurface materials observed from the landslide scarps were mostly silty clay. The active layer was about 1 m thick in the burned areas and thinner in the unburned area where intact trees and vegetation provide insulation to the subsurface soils. Permafrost extended to a great depth and the fine-grained permafrost soils were usually ice-rich.

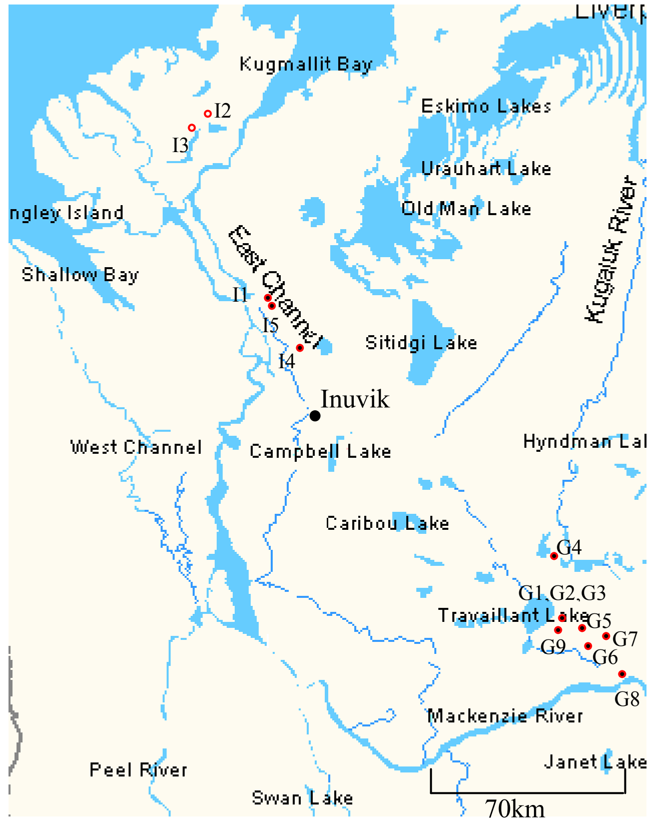


Figure 1. Site location map (dots with notation I1 to I5 and G1 to G9 indicate study site locations).

3. FIELD TEST PROGRAM

The field program was conducted during two trips to the sites. The first trip was from June 14 to 21, 2007, right after the spring breakup and the second trip was at the end of the summer from September 6 to 14, 2007. It should be noted that the ground surface was still covered by snow at the end of May 2007. Snow patches were still visible in some shaded areas during the June 2007 field visit. Survey stakes were installed on the ground at 20 m and 40 m upslope from the crest of each landslide visited in June 2007. It is believed that the summer retrogression of the landslides just started at the time of the June visit. Most of the survey stakes were measured again during the subsequent September visit. A few of them were not measured in September due to unfavorable weather conditions for site access by air. 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 movements of the landslides for the year 2007.

A large number of samples were also taken from the landslide sites during the field visits. Most of the samples were taken for soil moisture/ice content measurements at 10 cm intervals to a maximum of 2.8 m depth. Some other samples were taken for soil grain size analysis.

The geometries of the landslides and slopes were also measured during the field visits.

The results from the field programs are discussed in the following sections.

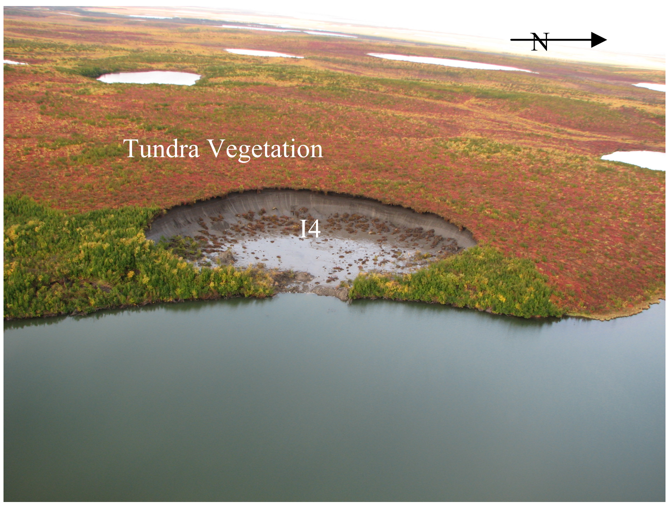


Figure 2. A typical landslide (I4) in tundra region affected an area of about 10,000 m^2 by 2007 and is still growing.

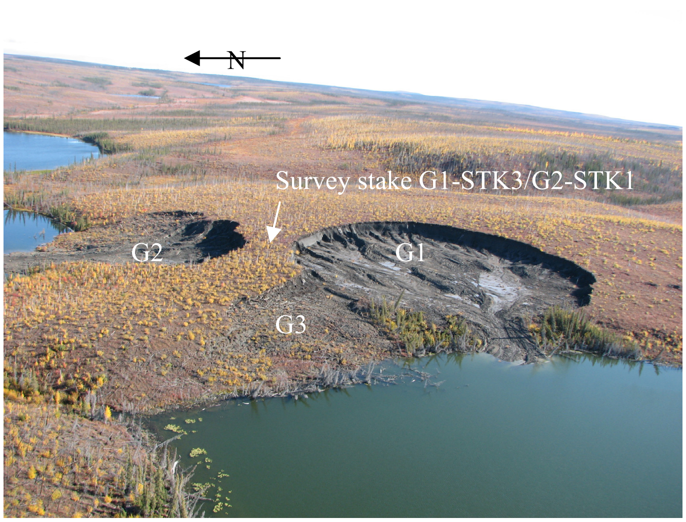


Figure 3. Typical landslides in burned forest area (note: G1 started a few years before 2004, exact time unknown; G2 likely started after G1; and G3 started in 2004; G1 and G3 merged together in 2006. A survey stake G1-STK3/G2-STK1 for measuring G1 and G2 was installed at the narrow point between G1 and G2).

Figure 4. A typical landslide (G8) in heavily forested region affected an area of about 30,000 m^2 by 2007. A small landslide initiated next to the large landslide.

4. RESULTS

4.1 Material properties

The gradations of the soil samples taken from seven test locations are shown in Figure 5. The materials are mostly silty clay or clayey silt. The samples from the southern sites (G series) are finer than those from the northern sites (I series).

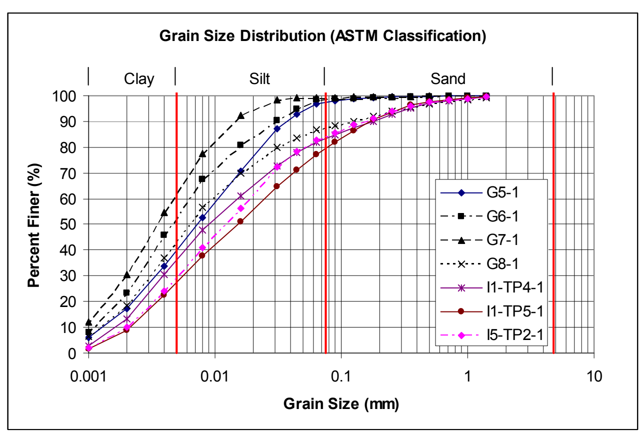
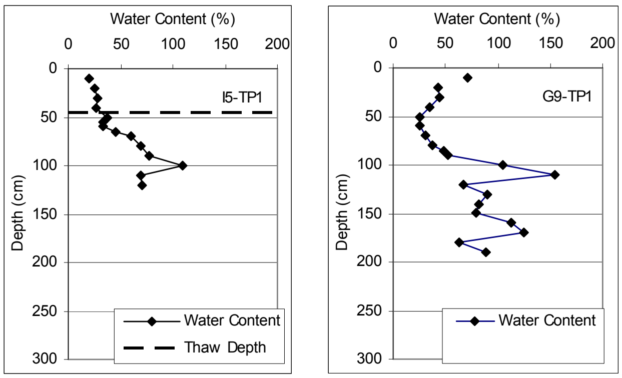


Figure 5. Grain size distribution of soils from the test sites.

The total water contents (including pore ice melt) of the soil samples were measured in the laboratory of the Geological Survey of Canada, Ottawa. Two typical soil moisture profiles for the northern and southern sites are provided in Figure 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 below the permafrost table of about 0.5 m depth at the northern sites and about 1.0 m depth at the southern sites.



(a) A northern site (I5) (b) A southern site (G9)

Figure 6. Typical soil moisture profiles.

4.2 Thawflow movement characteristics

The measured thawflow head scarp expansion rates are summarized in table 1 with slide geometries.

Table 1. Landslide scarp expansion during summer 2007

Site Location	Length of Slide* (m)	Width of Slide* (m)	Height of Wall (m)	Slope Angle (°)	Scarp Wall Dipping Direction	Scarp Moved by (m)
I1-STK	114	133	9.1	10.9°	N50°E	7.0
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
G5-STK2	138	95	8.2	7.0°	N70°W	7.0
G7-STK2	120	102	2.2	4.0°	N56°E	4.7
G6-STK2	125	115	6.4	6.0°	N18°E	6.5
G8-STK2	195	192	14.5	9.0°	N0°E	9.7

Note: * Length of slide was measured as the largest dimension from crest to lake; width was measured as the largest dimension perpendicular to slide direction.

The measured results of the slide retrogression rates ranged from 4.7 m to 9.7 m in the summer of 2007.

The thawflow retrogression rates are compared with the heights of the scarp walls of the slides as shown in Figure 7. The chart indicates an approximate correlation between the rate of scarp retrogression and the height of the scarp wall.

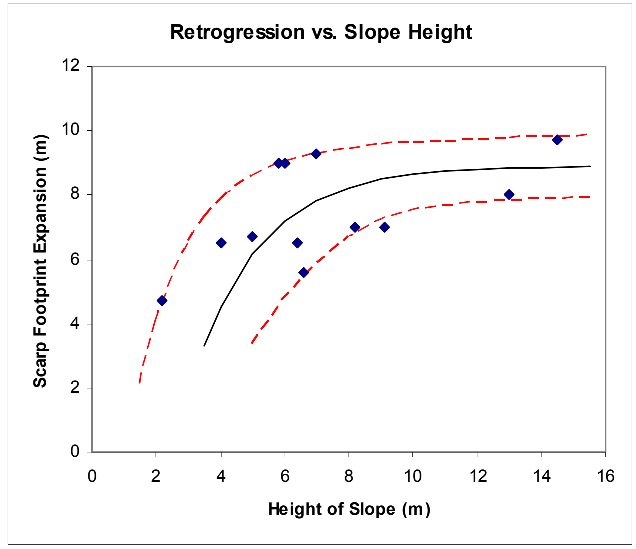


Figure 7. Relationship between landslide head scarp movement and height of scarp measured in 2007 (The dashed lines indicate envelopes and the solid line represents an approximate trend).

Although the data are somewhat scattered in Figure 7, there is a trend showing an increase of the thawflow retrogression rate with the increase of the scarp wall height. The two dashed lines represent a lower and an upper bound of the movement rate change with scarp wall height and the solid line indicates an approximate average trend. The maximum movement is limited to about 10 m for the year investigated.

As discussed earlier, thawflow process continues as long as ice-rich permafrost is exposed to the atmosphere. The slides with lower scarp walls expanded slower 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 the soil is usually ice-rich. The ice-rich soil becomes a liquid-like “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 and so does the flow rate. This causes the materials to build up at the toe of the scarp and cover part of the ice-rich permafrost. The reduced exposure of the ice-rich permafrost results in decreased amount of “slurry” being released from the melting scarp. As the sediment builds up at the toe of the scarp wall, so does the weight of the pile. When it is high enough, the built up mass flows away driven by its own weight. The covered ice-rich permafrost along the scarp wall is now exposed and melting of such permafrost is accelerated until it is covered again. The cycle repeats throughout the summer.

For slides with higher scarp walls, retrogression is faster. This is because: (a) The materials cannot build up high enough to block the ice-rich permafrost from melting; (b) The materials falling off the high scarp wall may have higher water content and therefore are more fluid and easier to flow. This is due to a higher ratio of ice-rich permafrost to active layer 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. Figure 7 indicates that maximum retrogression may occur for scarp walls higher than 6 to 8 m.

An attempt was made to compare slide retrogression with slope angle as shown in Figure 8. The slope angles were measured from the crests of the slides to the exit points of the thawflow at the lake shore. Although it shows that the rate of retrogression somewhat increases with slope angle, the trend is tenuous compared to that for the slope height shown in Figure 7. This can be explained as follows. The slope angle is usually greater near the lake shore and decreases with distance away from the lake, which is a typical feature of the gently rolling terrain in the region (Wang *et al.* 2005). Therefore, the overall slope angle measured from the crest usually decreases with the increase of the size of the slide. The height of the scarp wall is determined not only by the overall slope of the ground, but also by the slope of the flowing tongue within the landslide. A greater slope angle of the flowing tongue is related to lower water content in the flowing mass. It is translated to a lower flow rate and higher coverage of the scarp wall. This phenomenon is not reflected in the overall slope angle of the ground, but in the height of the scarp wall.

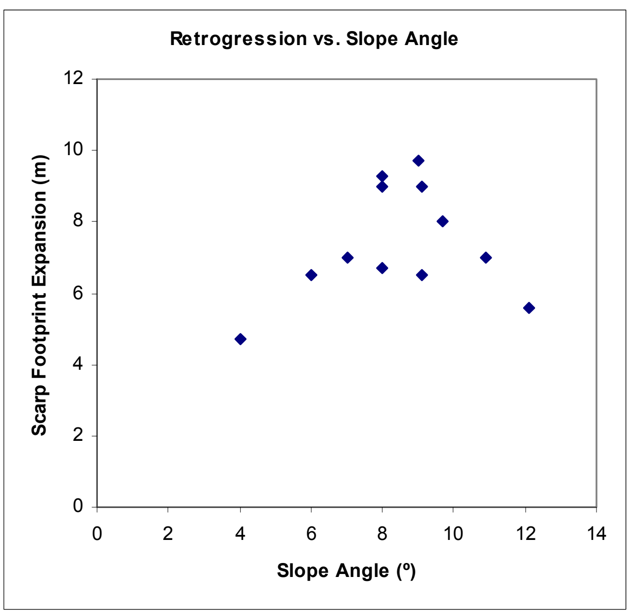


Figure 8. Rate of retrogression vs. slope angle (no obvious trend).

4.3 Influence of slope orientation

The dipping directions of the scarp walls where retrogression rates were measured are also shown in Table 1. The retrogression rates are plotted against the scarp orientations as shown in Figure 9.

Most displacements were measured at the highest scarp wall of the slides (usually at the highest ground elevation along the thawslide footprint). Some of them were at the side (or lateral) scarp walls, e.g., G1-TP2 and G1-STK3 in Table 1.

It should be noted that landslides G1 and G2 are next to each other flowing to two different lakes (Figure 3). G1 faces south-west and G2 faces north. Survey stakes G1-STK3 and G2-STK1 in Table 1 were installed at the same location for monitoring the movement of landslides G1 and G2, respectively. The portion of scarp wall of G1 monitored by G1-STK3 faced south and that of G2 monitored by G2-STK1 faced north. The measured results indicated exactly 9 m of scarp retrogression for both scarp walls. It means that landslide retrogression rate does not have any preference over south facing or north facing of the scarp wall for the same material.

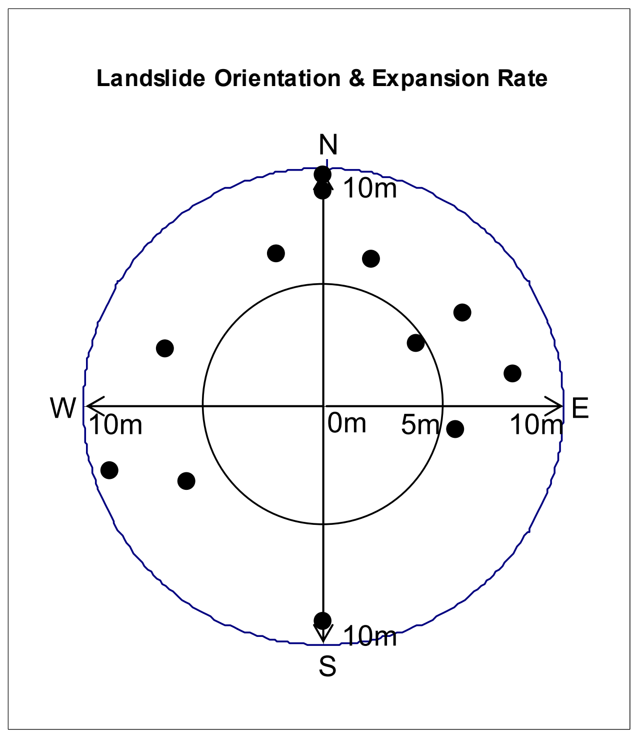


Figure 9. Relationship between scarp wall movement and orientation.

The slide-orientation relationship plotted in Figure 9 also shows that thawflow 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, north-east, north-west and south-west, observations from the field indicate that most of the thawflows are in circular shape (Wang *et al.* 2005). It means that the slides have been retrogressing evenly along the footprints, most of them with a portion of the wall facing south-east.

5. CONCLUSIONS

Thawflow retrogression in fine-grained permafrost is more influenced by the height of the scarp wall. The retrogression rate increases with increase in scarp wall height. The movement can be as great as 10 m per year. The rate does not increase further when the height of the scarp wall is greater than about 6 to 8 m.

Thawflow process does not have preference over slope orientation. In other words, north facing slides or scarp walls do not necessarily retrogress slower than south facing ones.

It should be noted that the results are based on one season field studies during the summer of 2007. It is believed that the results are representative, although some variations are expected with annual weather fluctuations.

6. ACKNOWLEDGEMENT

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