GELIFLUCTION WITHIN A SOLIFLUCTION LOBE
IN THE KÄRKEVAGGE VALLEY,
SWEDISH LAPLAND

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ABSTRACT. Soil displacement, soil temperature, depths of thaw plane and groundwater level were continuously monitored during the period from July 1999 to June 2000 within a solifluction lobe in the Kärkevagge valley, northern Sweden. The strain-probe method was used to measure soil displacement, and we found significant soil displacements in the thawing period 2000. These displacements were the result of gelifluction. The ice content profile showed that gelifluction occurred at the same time as the thaw plane reached the layers with high ice content at shallow soil depths (0–6 and 16–25 cm deep). In contrast, gelifluction did not occur when the thaw plane reached the layers with high ice content at greater depth (46–49 cm deep). These observations indicate that thawing of ice lenses in the near-surface layer triggers gelifluction.

Key words: gelifluction, ice lens, strain-probe, Kärkevagge

Introduction

Thawing of frozen soil results in slow movement of soil in spring. Washburn (1967) and Benedict (1970) proposed that soil movements occur due to two mechanisms: frost-heave followed by thaw-settlement (frost creep), and thaw-induced saturated flow (gelifluction). The mechanism of frost creep has since been examined by simultaneous monitoring of soil displacement and soil temperature (e.g. Matsuoka 1994, 1998a; Yamada et al. 2000). Models for estimating the rate of frost creep have also been presented using parameters such as slope gradient and material conditions such as grain-size and thickness of fine debris layer (Higashi and Corte 1971; Matsuoka 1998b).

In contrast to these in-situ instrumented studies for frost creep, studies to clarify the mechanism of gelifluction have been limited, except for simple observational research (e.g. Rapp 1960; Benedict 1970; Smith 1988) and laboratory experiments (e.g. Harris et al. 1995, 1997; Van Asch et al. 1989). These studies pointed out that an increase in soil moisture plays an important role in controlling the rate of gelifluction. However, owing to the lack of simultaneous data on soil moisture and soil movements in field sites, the mechanisms causing gelifluction still remain unclear.

This paper discusses the relation between the process of gelifluction and some influential environmental factors such as soil temperature, ice content and soil moisture, based on intensive field observations within a solifluction lobe in the Kärkevagge valley, northern Sweden. Among these environmental factors, we focus on the ice content in a seasonally frozen soil which may vary vertically in the soil profile.

Field setting

The solifluction lobe studied is located on the east-facing slopes around 800 m a.s.l. in the Kärkevagge catchment (Fig. 1a and b). These slopes are almost completely covered with vegetation, mainly of alpine meadow and heath types. The ground surface is usually covered with a seasonal snow cover from October to June in normal years. During spring, snow starts to melt from the bottom of the valley to the upper slope, providing snow melt water to the lower slope in springs.

A solifluction lobe located at an elevation of 770 m a.s.l. was studied intensively. The geometry is shown by a detailed topographic map (0.1 m contour interval; Fig. 2a). The inclinations of tread and riser are 24° and 46°, respectively. The ground surface of the solifluction lobe is almost covered with alpine meadow vegetation. We found a humus layer of 5 cm in thickness only on the tread (Fig. 2b). Below the humus, a layer with matrix-supported pebbles was found. Porosity, hydraulic conductivity, plastic limit, liquid limit of this layer and the grain-size distribution are shown in Fig. 2. The percent-
The age of the silt-clay contents was 23.7%. According to the classification by Kaplar (1974), this percentage corresponds to the boundary between frost-susceptible and non-susceptible soils.

**Method**
The following items were monitored: (1) temporal changes of surface soil temperature, (2) temporal changes of subsurface soil displacement and (3)
temporal changes in the depth to the thaw plane and
of the groundwater level.
Surface soil temperature and subsurface soil dis-
placement were measured hourly from July 1999 to
June 2000, and the data were recorded in a data-
logger. Surface soil temperature was measured by
a thermistor sensor with resolution and accuracy of
0.1°C and ±0.4°C, respectively.
Subsurface soil displacement was measured by
the strain-probe method (Williams 1957; Matsuoka
1994). The strain-probe was made from an elastic
strip of steel with width, thickness and length of 1.3
cm, 0.4 mm and 80 cm, respectively (Fig. 3). On
both sides, a pair of strain gauges (5 mm wide and
3 cm long) was attached. Two pairs of strain gaug-
es, which were attached in one segment of 10 cm in
length, configure a Wheatstone bridge circuit in or-
der to negate temperature-dependence error of the
strain gauge. Thirty-two strain gauges were used in
total.
This strain-probe was buried in a pre-excavated
trench and was directed perpendicular to the
ground surface. When soil displacements occurred
and thus the strain-probe was deformed, the probe-
logger system detected and recorded strain value.
The strain values from strain gauges were convert-
ed into soil displacements, assuming circular-
shaped bending of one segment, no discontinuity
between segments, and that the deepest edge of the
probe had been fixed during monitoring (Yamada
and Kurashige 1996). The probe-logger system
reads ±20000×10⁻⁶ strain with resolution and ac-
curacy of 1×10⁻⁶ strain and reads ±5×10⁻⁶ strain,
respectively. Since 0.25 mm of soil displacement in
one segment corresponds to 10×10⁻⁶ strain, more
than 1 mm of soil displacement can be used.
The soil displacement data obtained by the
strain-probe can be disturbed by vertical soil dis-
placements caused by frost-heaving and subse-
quently thaw-settlement processes (e.g. Yamada
1997; Sato et al. 1997). Soil temperature values
were used for determining whether the soil was
freezing or thawing. If the probe detects positive
(i.e. downslope) deformation during a freezing pe-
riod, this deformation should be due to frost-heave.
On the other hand, if negative (i.e. upslope) defor-
mation occurred during a thawing period, this de-
formation should be due to thaw-settlement. There-
fore, only positive deformation of the probe during
the thawing period should have been identified as
a net downslope displacement of soil.
Depths of both the thaw plane and the ground-
water level were monitored at approximately three-
day intervals from 28 May to 30 June 2000, using
an iron pole and an electric tester. The iron pole
penetrated into the soil until it reached a hard layer
that corresponded to an ice surface, i.e. a thaw
plane. The groundwater levels were confirmed by
a change in electric conductivity.
Weight percentages of ice content in the season-
ally frozen soil were also estimated. The cored
sample for analysis was obtained by a hand-type
drilling machine on 29 May 2000, when the snow
cover almost disappeared from the surface. The
core (67 cm in length, 5 cm in diameter) was cut
into segments approximately 5 cm in length and
then all the segments were weighed at the field site.
By comparing this weight with that of the dried
samples, the ice content was estimated.

Results
The soil surface temperature and soil displace-
ments are shown in Fig. 4. The ground surface start-
ed freezing in late November 1999 and did not thaw
until 28 May 2000. Six freeze–thaw cycles of diur-
nal freeze–thaw occurred during the thawing peri-
od (late May to mid-June 2000; Fig. 4a).
Soil displacement occurred in accordance with
the seasonal freeze–thaw cycle. A significant
downslope displacement occurred during the freezing period of 1999, whereas an upslope displacement occurred during the thawing period of 2000. Referring to annual ground temperature cycle, this downslope–upslope fluctuation was probably due to frost-heave and resultant thaw-settlement.

Even in the trend of upslope displacement during the thawing period of 2000, two events of significant downslope displacements, which correspond to approximately 1 cm downslope displacement, were detected on 30 to 31 May and 3 to 4 June (events 1 and 2 in Fig. 4b). Because these events occurred during a thawing period, these displacements were probably induced by gelifluction.

Figure 4c shows the temporal change in the depth of the thaw plane and of the groundwater level during the thawing period. The thaw plane was at 13 cm depth on 28 May when the snow cover dis-
appeared. Thereafter the depth of the thaw plane slightly increased by several centimetres per day. On 27 June, the depth of the thaw plane reached more than 80 cm. The groundwater level remained nearly constant at the ground surface, suggesting that the thawed layer was saturated almost throughout the thawing period.

Figure 5 shows the vertical profile of the weight percentage of ice content in the seasonally frozen soil. The maximum value of 35.6% was found in the uppermost layer with 6 cm in thickness. The second and third maximum values were found at 16 to 25 cm depth (26.2%) and at 46 to 49 cm depth (23.9%), respectively. The relatively high ice contents indicate the existence of ice lenses within these layers.

**Discussion: significance of melting of ice lens for gelifluction**

The role of thawing ice lenses for gelifluction has been stressed by some authors (e.g. Williams 1959; Harris 1977). Thawing of the ice lenses not only provides water, but results in discontinuities where the strength of cohesion and/or shear strength is comparatively reduced. Thus, thawing of the ice lenses probably results in gelifluction, although no conclusive evidence has been presented.

The present study first found field evidence of the role of thawing ice lenses for gelifluction at shallow soil depths. The soil displacement events occurred when the thaw plane reached the layer of high ice content. When the soil was significantly displaced (i.e. event 1:30–31 May), the thaw plane was close to the surface where the ice content was highest in the sampled cores (Fig. 5). Next, significant soil displacement (i.e. event 2:3–4 June) also occurred when the thaw plane reached the layer with moderately high ice content (Fig. 5).

At greater depths, on the other hand, gelifluction did not occur even when the thaw plane reached the layer of high ice content. Soil displacement was not detected around 15 June, when the thaw plane reached the layer of relatively high ice content (i.e. depth between 46 and 49 cm; Fig. 4c). This indicates that thawing of the ice lenses at greater depths does not trigger gelifluction. This fact has been predicted by the laboratory experiments of Harris and Davies (2000). They found that the potential of gelifluction was likely to decrease with depth, owing to increase of shear strength and decrease of the void ratio of soil.

The present study found evidence for the role of thawing ice lenses for gelifluction through field observations. Incorporating physically based gelifluction models (Van Asch et al. 1989; Kirkby 1995) and frost-creep models (Higashi and Corte 1971; Matsuoka 1998b), our findings will help to develop a general model to predict soil displacement on mountain slopes where freeze–thaw cycles occur.

**Concluding remarks**

The results and discussions can be summarized as follows.

1. Two events of soil displacement during the thawing period were detected by the strain-probe and were regarded as gelifluction.
2. The gelifluction simultaneously occurred when the thaw plane reached a layer of high ice content.
3. Thawing of ice lenses at shallow depth triggers gelifluction.

The roles of thawing ice lenses should be included in the general modelling of soil displacement in mountain slopes where seasonal frost occurs.

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