Study of Ice-Rich Syngenetic Permafrost for Road Design (Interior Alaska)

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Abstract

Geotechnical investigations along the proposed alignment of the Dalton Highway between MP 8 and MP 12 included core logging and laboratory testing of soil samples. The cryofacies method by Katasonov was used to identify the origin of permafrost. Ice-rich syngenetic permafrost with large ice wedges (yedoma) in the area was formed in the late Pleistocene by simultaneous accumulation of silt and upward permafrost aggradation. Four sections with different properties of frozen soils were distinguished. Thickness of ice-rich silt varied from several meters to more than 26 m, and the wedge-ice volume can be nearly 50%. Extremely high ice content of syngenetic permafrost determined its high thaw susceptibility. Thaw strain varied from 20% to 60%. Yedoma soils in the study area are separated from the base of the active layer by two protective layers: a 0.5- to 1-m-thick ice-rich intermediate layer, and a 1- to 4-m-thick ice-poor layer of thawed and refrozen soils. Road construction can cause thaw settlement and slope failures in cut areas.

Keywords: Alaska; geotechnical investigations; ice wedges; syngenetic permafrost; thaw settlement; yedoma.

Introduction

The Alaska Department of Transportation (AKDOT) recently proposed a new alignment of the Dalton Highway between Mile Post (MP) 8 and MP 12 (Fig. 1). The study area is located approximately 20 km north-west of Livengood and about 100 km north of Fairbanks. The Trans-Alaska Pipeline in this area is located about 2 km east of the Dalton Highway. The area is drained by the Yukon River and belongs to the Yukon-Tanana Upland formed by generally rolling low mountains (Wahrhaftig 1965). The 4.5-km-long alignment is sloping gently to the northwest from approximately 470 m to 320 m above sea level.

The proposed alignment crosses the area with extremely complex permafrost conditions. The Alaska University Transportation Center (AUTC) of the University of Alaska Fairbanks (UAF) was involved in geotechnical investigations for this project. An analysis of existing data from previous geotechnical investigations in the area identified the existence of ice-rich permafrost including massive ice. Boreholes drilled for the Trans-Alaska Pipeline in 1970 (Kreig & Reger 1982) showed the presence of more than 18 m of ice-rich silt. Large ice wedges were exposed nearby during construction of the Dalton Highway (Lotspeich 1971, Smith & Berg 1973).

In the 1990s, AKDOT investigated geotechnical conditions in the area to find a safer alignment between MP 8 and MP 12. In 1990, 45 test holes were drilled, and an additional 29 test holes were drilled in 1991. It was found that permafrost in the study area was continuous, and the thickness of massive ice varied from less than one meter to dozens of meters; high

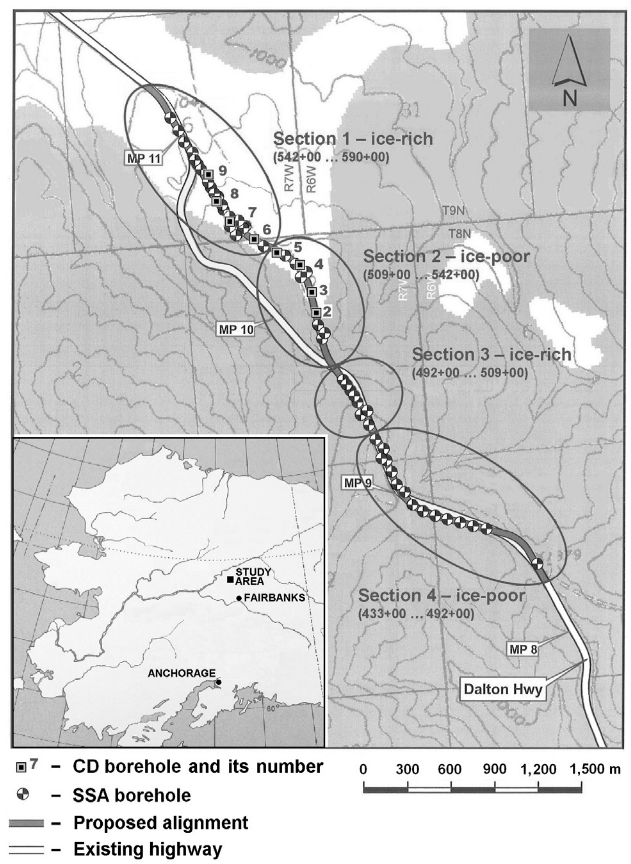

Figure 1. Location of the proposed alignment of the Dalton Highway and position of boreholes drilled in 2008.

contents of ice and organic matter were reported (Schlichting & Darrow 2006). In this paper, we present the main results of geotechnical investigations performed in the project area in 2008 as a cooperative effort between AUTC and AKDOT.

Methods

Hollow stem core drilling (CD) was conducted in May 2008 with a drill rig equipped with a modified CME (Central Mine Equipment Company) sampler (5 cm inside diameter). Eight CD boreholes (Fig. 1) from 7.5 m to 21.5 m deep were cored by an AKDOT crew (drillers Tom Johnson and Jason Cline) and logged by the authors (Shur et al. 2010). The total length of all cores was 109.4 m. An additional 54 boreholes, with a maximum depth of 26 m, were drilled without coring by solid-stem augering (herein referred to as SSA boreholes) and logged by AKDOT personnel (Rowland 2010).

For geotechnical investigations in areas with ice-rich permafrost, specific methods of permafrost field studies have been successfully applied. In this work, we used the cryofacies method (Katasonov 1969, 1978). This method is based on a close relationship between the shape, size, and spatial pattern of ice inclusions in soils (i.e., cryostructures) and specific terrain units, and reveals the nature of permafrost formation. The study of cryostructures allows researchers to identify the nature of permafrost and to estimate the ice distribution within it. The cryofacies method has been especially useful for study of syngenetic permafrost (Katasonov 1969, 1978, Shur & Jorgenson 1998, Kanevskiy et al. 2008, 2011). For description of soil cryogenic structure, we used a classification of cryostructures (patterns formed by ice inclusions in the frozen soil) that was adapted from several Russian and North American classifications (Gasanov 1963, Katasonov 1969, Kudryavtsev 1978, Zhestkova 1982, Shur & Jorgenson 1998, French & Shur 2010). Particle size distribution analyses were performed on 25 samples obtained from six CD boreholes (CD-2–CD-7) according to ASTM D 422 to quantify particle size distribution.

Wedge-ice occurrence and its distribution with depth were evaluated on the basis of data from 8 CD and 54 SSA boreholes. Ice content of frozen soil between ice wedges was evaluated by soil oven-drying (90°C, 72 h). Gravimetric moisture contents (on a dry-weight basis) were calculated for 189 soil samples. For volumetric moisture contents, 99 samples with accurate sample volume measurements were prepared. Thaw strain of ice-rich soil without external load was studied on 44 samples, and a consolidation test of thawed soils upon different loads was performed on five samples.

Results and Discussion

Area description

The study area is located within the discontinuous permafrost zone (Péwé 1975, Jorgenson et al. 2008). Permafrost temperatures at the site vary from -1.5°C to -0.5°C (Rowland 2010). Active layer thickness varies mostly from 0.5 to 1 m. There is no contemporary growth of ice wedges in the area. Wedge-ice development in Interior Alaska can be expected only in organic soils, usually on flat surfaces with limited drainage and mostly in peat bogs (Hamilton et al. 1983). Despite the recent forest fire (2003 Erickson Creek fire) and subsequent increase in the active layer thickness, thermokarst features in the project area are limited to shallow irregular thermokarst scars; thaw settlement does not exceed 0.5 to 1 m. We did not observe any distinct thermokarst troughs above melting ice wedges using both high-resolution aerial photographs and our surface observations. Numerous old gullies in the study area have not shown any evidence of the recent rejuvenation.

Soil characteristics

The surficial deposit is frozen silt (loess). The particle-size distribution analysis of the sediments from six boreholes (CD-2–CD-7) performed on 25 samples showed that the content of silt particles comprised 70% to 80% of bulk soils. The percentage of sand did not exceed 15%, and clay content varied between 10% and 20%. According to loss-on-ignition measurements by AKDOT (Rowland 2010), organic matter content varied from 2% to 20% with an average value of 6.7%. In most CD boreholes, horizons of organic-rich silt and peat were encountered at different depths. Thickness of silt varied from 0.5 m to more than 26 m. Radiocarbon age of sediments ranged from 22,600 to 43,100 yr BP (eight samples were obtained from the CD boreholes). Radiocarbon ages of similar sediments from 18,000 to 27,000 yr BP were reported for the adjacent area (O'Donnell et al. 2011). Silt deposits are underlain by colluvial and fluvial gravelly soils up to 3 m thick or weathered bedrock. Bedrock in the study area is represented mostly by highly deformed weathered sedimentary rocks. Neither CD nor SSA boreholes (the deepest hole was about 26 m deep) located at the base of the slope at elevations from 320 to 380 m reached the base of silt deposits.

Cryogenic structure and ice content

Study of the cryogenic structure of cores obtained from eight CD boreholes showed the prevalence of micro-cryostructures typical of syngenetic permafrost (Kanevskiy et al. 2011). An example of cryostructures and properties of soil between the ice wedges studied in one of the boreholes is shown in Figure 2. Soil presented here can be divided into the following cryostratigraphic units: (1) active layer (0–0.71 m); ice-rich intermediate layer (0.71–1.50 m); (2) ice-poor thawed and refrozen sediments (1.50–3.05 m); (3) ice-rich syngenetic permafrost (3.05–10.00 m); and (4) ice-poor epigenetic permafrost (10.00–12.20 m).

Most of the other CD boreholes revealed a similar structure of the upper permafrost. Five of eight boreholes showed a well-developed ice-rich intermediate layer (Shur 1988) from 0.7 m to 1.0 m thick. A rudimentary intermediate layer up to 0.3 m thick was encountered in two more boreholes. We related the formation of these poorly developed layers to the recovery of the upper permafrost after the forest fire, which had triggered an increase in the active layer thickness and degradation of the original intermediate layer.

In five boreholes, the ice-poor layer of thawed and refrozen sediments (ranging from 0.3 to 8.0 m thick) was encountered

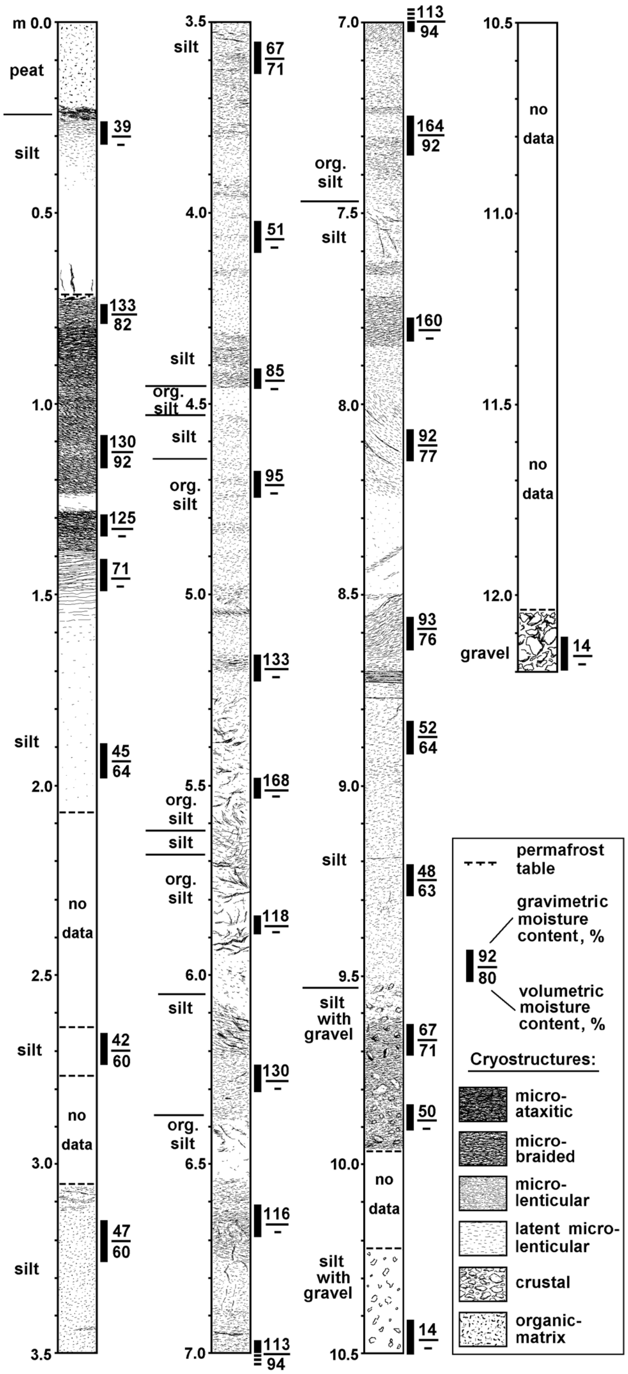

Figure 2. Cryogenic structure and ice content of frozen soils, borehole CD-4 (ice is black).

below the intermediate layer. The wide occurrence of thawed and refrozen sediments in Interior Alaska was previously documented by Péwé (1975). Wedge ice was encountered at various depths in all boreholes except CD-2, CD-4, and CD-5. In boreholes CD-8 and CD-9, ice wedges appear just below the ice-rich intermediate layer, from depths 1.2 m and 1.5 m respectively. Soils between ice wedges are mostly ice-rich. The wide range (from ~40% up to 200% and more) and high values (85.5% average) of gravimetric moisture content, which do not change significantly with depth, are typical of syngenetic permafrost.

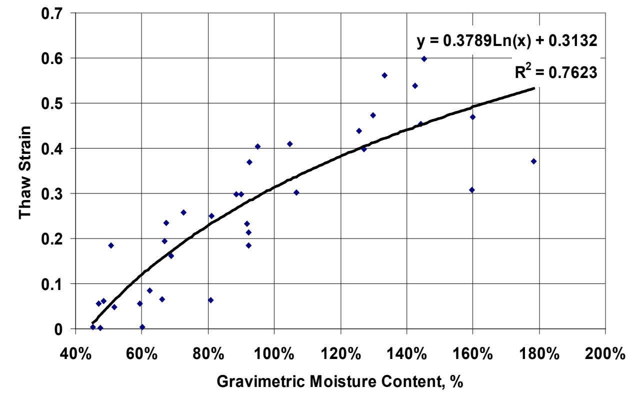

Figure 3. Logarithmic relationship between thaw strain of mineral soil (without external load) and gravimetric moisture content (based on the data for 35 samples from CD boreholes).

Thaw strain

Evaluation of thaw strain of frozen soils was based on 44 tests of thawing without external load (free thawing) and five consolidation tests. Average thaw strain was 0.23. Average thaw strain values for mineral and organic soils were 0.26 (35 samples) and 0.13 (9 samples) respectively. Figure 3 shows the correlation between thaw strain and gravimetric moisture content for 35 samples of mineral soils. We found that organic soils behaved differently from mineral soils, and their thaw strain in free thawing was much lower. In consolidation tests, the part of the thaw strain of organic soils related to the impact of a load was greater than that of mineral soils, and the total thaw strain of organic-rich silt was comparable to the thaw strain of mineral soils.

Wedge-ice volume and identification of alignment sections with different permafrost characteristics

Wedge ice is the main type of ground ice in syngenetic permafrost and the only one identified in boreholes in the studied area. Gray- and brown-colored wedge ice with a distinct vertical foliation due to mineral and organic inclusions was encountered at various depths in both CD and SSA boreholes. Our experience shows that during the drilling in the areas with the ice-rich syngenetic permafrost (yedoma), wedge ice can be found at different depths. It can be related to the occurrence of ice wedges buried at different depths, irregular boundaries of ice wedges, variability of the wedges' thickness with depth, and inclination of wedges. The penetration of wedges through the entire silt stratum is typical of yedoma. Wedge ice was found in most of the CD and SSA boreholes, but its occurrence varied along the alignment. On the basis of the wedge-ice occurrence, we identified four sections, two of which (sections 1 and 3) are defined as rich in massive ice and two (sections 2 and 4) defined as poor in massive ice. Boundaries between these sections are shown in Figure 1. A cryostratigraphic profile for sections 1 and 2 of the study site is shown in Figure 4**.**

Section #1 was characterized by the sequence of ice-rich syngenetically frozen silt from 12 m to more than 26 m thick. Wedge ice was observed at various depths in 24 of

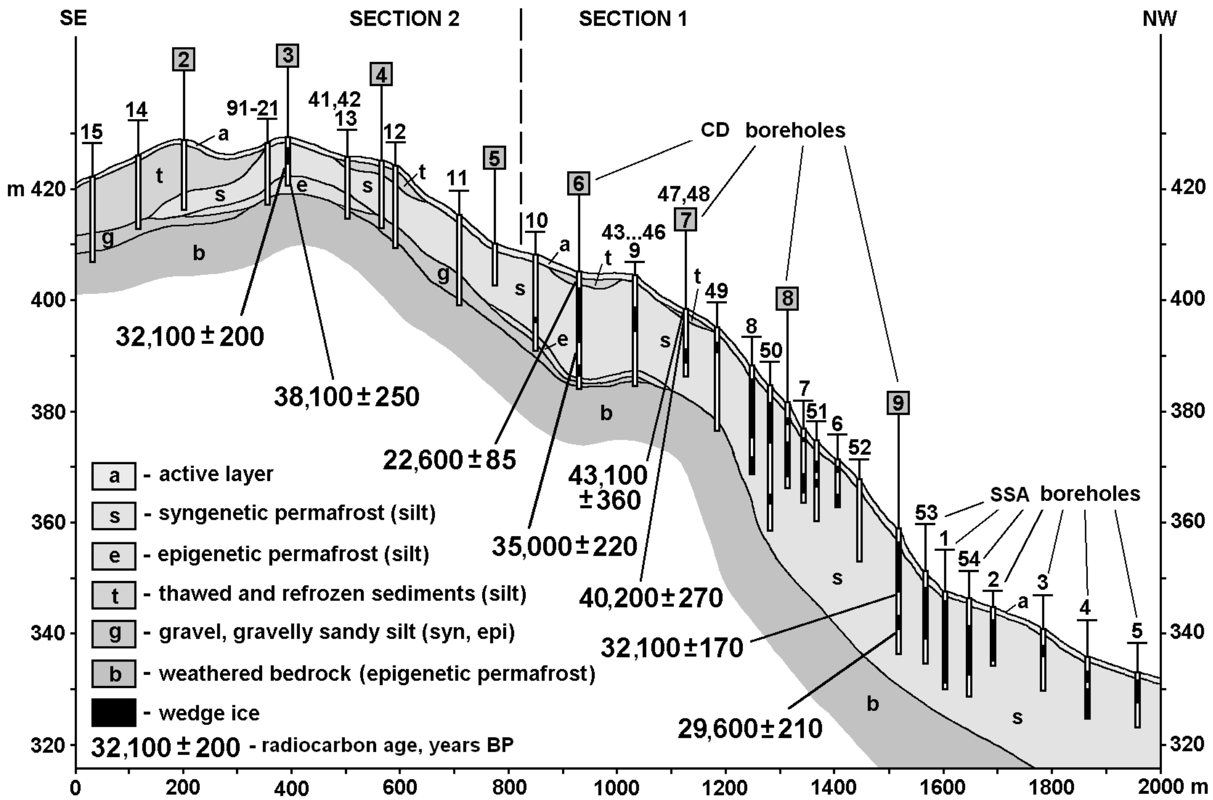

Figure 4. Cryostratigraphic profile. CD boreholes are marked by squares, and the rest are SSA boreholes.

26 boreholes. Average wedge-ice occurrence in this section reached 35%, but the wedge-ice volume was not distributed evenly with depth. Absence of ice wedges in the upper meter of the sequence can be explained by the occurrence of an intermediate layer beneath the active layer. Relatively small wedge-ice volume (less than 15%) at a depth interval of 1 to 2 m occurs in the ice-poor layer of thawed and refrozen soils. The highest values (more than 40%) were at depth intervals from 6 to 10 m and 17 to 20 m. Average gravimetric moisture content of silt between ice wedges was 102% (based on measurements of 85 samples from four CD boreholes). The lowest values of moisture content were obtained mostly at the depth interval from 0 to 3 m (they correspond to the active layer and the layer of thawed and refrozen sediments). The estimation of average thaw strain due to segregated ice was 0.32, so the total thaw strain (due to wedge ice and segregated ice) was 0.56. This thaw strain estimation was not conservative because it reflected only the settlement upon thawing without load.

In the ice-poor section #2, wedge-ice was found in only one of 12 boreholes at depths ranging from 1.8 to 4.8 m, and wedge-ice occurrence in this section was about 2%. Syngenetic permafrost was identified in every CD borehole in section #2, although it can be overlain by the layer of thawed and refrozen sediments up to 9 m thick. The thickness of silt in this section varied from 10 m to 12 m. Ice content of the soil in section #2 is 79% (based on measurements of 88 samples from four CD boreholes), which is lower than in section #1. The lowest values corresponded to the active layer and the layer of thawed and refrozen sediments. The average thaw strain due to segregated ice was 0.23, and the total thaw strain estimation was 0.25.

In the ice-rich section #3, wedge-ice was found in 8 of 9 boreholes and occupied 47% of the combined length of all boreholes. Wedge-ice was not observed from 0 to 2 m, and from 2 to 4 m its volume did not exceed 17%. We relate this to occurrence of the ice-poor layer of thawed and refrozen soils. Wedge-ice volume more than 50% was observed from 6 to 14 m, and at 8 to 14 m it reached more than 80%. The thickness of silt in this section varied from 9 to 14 m. Average gravimetric moisture content of the silt was 81% (based on measurements of 38 samples from nine SSA boreholes). The lowest values of soil moisture content were obtained mostly at the depth interval from 0 to 4 m (they correspond to the active layer and the layer of thawed and refrozen sediments) and from 12 to 17 m (gravelly soil and bedrock). The average thaw strain due to segregated ice was 0.23, and the total thaw strain was 0.59.

In the ice-poor section # 4, wedge ice was found in one of 15 boreholes. Wedge-ice occurrence is very small (about 3%), but the gravimetric moisture content of perennially frozen silt is relatively high (63% average, based on measurements of 21 samples obtained from 15 SSA boreholes). This section was characterized by a 0.5- to 4-m-thick sequence of silt overlaying gravel and weathered bedrock. The average thaw strain due to segregated ice was 0.13, and total thaw strain was 0.16.

Genesis of permafrost

Our study of soils and ground ice show that the frozen silt in the study area is mostly ice-rich syngenetic permafrost formed in the late Pleistocene (yedoma). The evidence includes thick deposits of homogeneous silt with poorly decomposed organic matter, age of sediments (22,600 to 43,100 yr BP, Fig. 4), very high ice content, prevalence of micro-cryostructures, and occurrence of large foliated ice wedges penetrating through the entire silt sequence. Yedoma deposits were formed by simultaneous accumulation of windblown silt partly reworked by slope and fluvial processes (Péwé 1975) and upward permafrost aggradation. Ice-rich syngenetic Pleistocene permafrost widely occurs in Interior Alaska, on the Seward Peninsula, and on the Arctic Foothills of the Brooks Range, and it can be encountered in other areas that had remained unglaciated during the late Pleistocene (Kanevskiy et al. 2011). Until recently, this type of permafrost has been understudied in Alaska, and investigations for engineering projects usually do not provide sufficient information for its characterization. In Interior Alaska, the cryogenic structure of these sediments has been studied extensively in the well-known CRREL permafrost tunnel at Fox, near Fairbanks (Sellmann 1967, Hamilton et al. 1988, Shur et al. 2004, Bray et al. 2006, Fortier et al. 2008, Kanevskiy et al. 2008). A comparison of ice-rich soils in the study area with those of the CRREL permafrost tunnel showed that they had similar age, cryogenic structure, and ice content. Wide occurrence of yedoma in Alaska presents a great challenge to development and should be closely considered during geotechnical investigations in Interior Alaska.

Conclusions

The thick layer of syngenetic permafrost in the studied area was formed during the late Pleistocene by simultaneous accumulation of silt and upward permafrost aggradation. Most of the soils in the project area are extremely ice-rich and display excessive thaw settlement upon thawing. The thickness of ice-rich silt usually varies from 10 m to more than 26 m, and wedge-ice volume can reach more than 45%. Extremely high ice content of syngenetic permafrost with ice wedges determines its high thaw susceptibility. Thaw strain values generally vary from 20% to 60%. Four sections with different permafrost properties are identified along the proposed alignment. Sections #1 and #3 are extremely ice-rich, and permafrost thawing in these parts of the alignment will bring significant thaw settlement. Ice wedges in sections #2 and #4 are rare, but thaw settlement of silt cannot be neglected. The main potential hazards related to road construction in this area are (1) significant differential thaw settlement of soils beneath the road; (2) rapid retreat of permafrost slopes in cut areas resulting in slope failures; and (3) contamination of surface water due to thawing of organic and ice-rich silt at the slopes. Mitigation of these hazards will result in extremely high maintenance costs.

Ice-rich soils with large ice wedges are usually separated from the base of the active layer by two protective layers: a 0.5- to 1-m-thick ice-rich intermediate layer, and a 1- to 4-m-thick ice-poor layer of thawed and refrozen soils. Formation of the latter could be related to climate changes during the Holocene or to frequent wildfires. Occurrence of the ice-poor layer on top of the ice-rich syngenetic permafrost is extremely important for resilience of ecosystems to environmental changes and to the integrity of the road in fill areas. In cut areas, this protective layer can be completely destroyed, and permafrost becomes thaw sensitive and vulnerable to climatic impacts and local disturbances. The ice-poor layer is favorable to stabilization of exposed permafrost slopes in cut areas.

Acknowledgments

This work was funded by the Alaska University Transportation Center (project #207122) and the Alaska Department of Transportation. Data analysis was also supported by the National Science Foundation (NSF grant EAR 0630257). We appreciate the good job done by AKDOT drillers Tom Johnson and Jason Cline, cooperation in the field with AKDOT geologists Julie Rowland and Ronald Brooks, and discussion at the different stages of the project with AKDOT engineers and geologists Jessie Reinikainen, Steve Masterman, James Sweeney, and Leo Woster. We also thank Vladislav Roujanski and James Rooney for valuable comments and suggestions.

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