Vulnerability of the north Alaska Highway to permafrost thaw

Design options and climate change adaptation

Northern Climate ExChange
YUKON RESEARCH CENTRE · Yukon College

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1. INTRODUCTION

The Alaska Highway between Burwash Landing and the Yukon/Alaska border is underlain by extensive discontinuous, warm and frequently ice-rich permafrost. The disturbance caused by construction of the road and climate warming has already led to the thawing of permafrost, which has had an impact on the road. Some sections of the highway have experienced longitudinal cracking, embankment failure, differential settlement and even complete collapse. In order to better understand these issues, the Yukon Government Department of Highways and Public Works (HPW) has partnered with the Northern Climate ExChange in a four-year project (2012-2016) to assess permafrost sensitivity to thaw under the northern 200 km of the Alaska Highway. Since its construction, this section of highway has been affected by permafrost thaw. In the context of current and anticipated climate change, permafrost temperature is warming and is expected to continue to rise (SNAP 2014). Faster and more extensive permafrost thaw will result in an increase of frequency and magnitude of the damage sustained by the highway.

The first three years of the project had three goals: 1) to identify and characterize sensitive permafrost areas underlying the highway; 2) to establish potential future climate scenarios for the study region; and 3) to estimate the potential impacts of the identified climate scenarios where the highway is underlain by thaw sensitive permafrost. The outcome of the assessment was a reference document that can be used to support decisions regarding road maintenance and future measures to mitigate permafrost thaw. It represented the first step to address the upcoming impact of the climate change on the Alaska Highway at a regional scale.

The final year of the project was to design permafrost thaw remediation strategies in critical areas. Using the findings from the vulnerability assessment, as well as results from the Beaver Creek permafrost test site, the final year of the project (2015-2016) aimed to determine the most suitable techniques for a selection of thaw-sensitive sections of highway anticipated to be responsive to remediation, and to develop recommendations and preliminary adaptation designs for these sites.

The Beaver Creek permafrost test strip was constructed in 2008. It is part of an on-going project that is funded by NSERC and twelve public and private sector partners, including HPW. The goal of the test strip is to improve current adaptive methods for transportation corridors by testing techniques aimed at mitigating permafrost instability. The test strip is 600 m long, and is subdivided into twelve instrumented test sections that focus on activation of heat extraction during winter, or reduction of heat intake during summer (e.g., air convection embankments, heat drains, longitudinal culverts, sun/snow sheds, albedo reduction techniques, embankment snow clearing, etc.). The site is heavily instrumented with thermistors, surface temperature loggers, groundwater sensors and weather monitoring equipment.

The thaw mitigation and remediation techniques being tested at the Beaver Creek site offer some of the most realistic and feasible adaptation options for responding to permafrost thaw along the Alaska Highway. Using the vulnerability assessment to select suitable sites for implementing adaptation techniques that have proven efficiency in the same area constitutes an important next step in achieving broader-scale implementation of these adaptation techniques, and therefore contributes to the strengthening of HPW's adaptive capacity and ability to respond to climate change impacts.

1.1 REPORT OUTLINE

This project builds on the first three years of the project team's research which provided descriptions of permafrost characteristics underneath the highway on a section-by-section basis. As stated, the major output of the project will be to develop enhanced adaptation options for HPW through recommendations regarding remediation and/or mitigation techniques for priority sites along the Alaska Highway. It will also include the site-specific development of preliminary designs for the recommended techniques. A full cost-benefit analysis and detailed engineering designs will be required before any installations are done; this element does not fall within the scope of this project. The target audience for the report from this final project year targets civil engineers.

The report is structured as follows:

- Section 1 provides an introduction to the report.
- Section 2 describes the field methodology used to assess permafrost vulnerability to thaw.
- Section 3 introduces technologies and approaches used to mitigate permafrost thaw.
- Section 4 reviews the proposed adaptation options for a selection of sites expected to be responsive to implementation of thaw mitigation and remediation. This includes details regarding the existing highway design, characterization of permafrost state, and design options for adaptation at the site.
- Section 5 provides a brief summary of findings in the report.

The authors have attempted to minimize the use of scientific terminology in order to ensure broad understanding of the results. It is hoped that the contents of this report will be used to develop strategies to adapt to climate change and mitigate the hazards associated with ground settlement.

2. METHODOLOGY

Three main tasks were performed to select sites and design the adaptation strategies for these sites:

1. Identification of areas potentially responsive to mitigation/remediation techniques.
2. Selection of priority sites for mitigation/remediation.
3. Development of mitigation/remediation recommendations and preliminary designs.

2.1. IDENTIFICATION OF AREAS POTENTIALLY RESPONSIVE TO MITIGATION/REMEDIATION TECHNIQUES

Using the vulnerability assessment that was the product of the first three-years of the project, areas that require and may be responsive to thaw mitigation or remediation techniques were identified. Known permafrost characteristics, current thaw sensitivity, current highway stability, degree of existing degradation, and local surficial geology and hydrology conditions, were considered, among other factors.

Areas of interest are highly vulnerable to thaw, may already be degrading, and will continue to be affected by thaw for multiple decades. This will cause heavy damage before permafrost degradation is complete. In some areas, it may take decades before any degradation takes place. However, once the permafrost table lowers enough to reach ice-rich ground, the impact of thaw will be substantial. Such permafrost areas are more likely to respond to thaw mitigation or remediation techniques, rather than those with thaw sensitive permafrost where permafrost has been almost completely degraded, or areas where permafrost appears to minimally thaw-sensitive.

Six sites were pre-selected based on the permafrost characteristics detailed in the Alaska Highway vulnerability assessment. Three sites had already been subject to detailed investigations, while three other sites never had been assessed in detail before. The sites underwent a site-specific assessment based on field investigations and laboratory analyses. Methods mirrored those used during the earlier vulnerability assessment.

2.2 SELECTION OF PRIORITY SITES FOR MITIGATION/REMEDIATION

The purpose of this task was to work from the list of six sites identified in the first step to shortlist the most appropriate sites for the implementation of larger-scale (relative to the Beaver Creek test site) mitigation and rehabilitation techniques. This phase of research included field investigation focusing largely on the acquisition of new geophysical information using electrical resistivity tomography (ERT) surveys. In addition, shallow drilling was used to verify interpretations of geophysical information and to develop cryostratigraphic logs. Importantly, the work focuses on areas proximal to the toe of the highway embankment and at the top of the embankment, along the shoulder parallel to the highway, where minimal information is currently available. This information is key because it will allow project researchers to infer the probability of permafrost presence under the highway embankment. Deeper drilling completed by contractors for HPW allowed the research team to confirm geophysical interpretations and field observations.

2.2.1 Permafrost drilling and sample collection

A light and portable GÖLZ Earth-drill system was used to drill shallow boreholes. It was coupled with coring tools that were designed and enhanced over the years at Centre d'études nordiques (CEN) of Université Laval in Quebec City and the Department of Earth and Atmospheric Sciences (EAS) of University of Alberta in Edmonton.

Boreholes were initiated by shoveling a fore hole down to the thaw front. At the thaw front, the Earth-drill system drill was used. The drill was mounted on a small Stihl engine with a high-speed transmission (600 rpm). Stainless steel rods that are 1 metre in length and 4.5 cm in diameter were connected to a core barrel that is 40 cm long and 10 cm in diameter, with diamonds set in carbide alloy teeth. This made it possible to drill in unconsolidated, fine- to medium- grain material (sand to clay). A core catcher was used to extract frozen core from the borehole, allowing for the collection of continuous, undisturbed permafrost samples. This type of drilling was limited to a maximum drilling depth of approximately 5 to 6 m under optimal conditions. In order to drill boreholes to deeper depths, a conventional water-jet diamond drill was used. Details regarding these tools and the drilling methodology are provided in Calmels, Gagnon and Allard (2005).

A total of three boreholes were drilled using this technique. The same sampling and drilling protocols were followed for each borehole. The site was first described (e.g., hydrology, vegetation type and density, topography), photos were taken, and locations were recorded using a hand-held GPS. Each core sample was photographed and described in situ (e.g., soil type, soil moisture, presence or absence of organic matter, any notable features). Each sample extracted from a borehole was identified by borehole name and depth. Samples were put in polybags and sealed immediately after being extracted. Samples were kept frozen and stored in a freezer that was taken back to the laboratory for further analyses. At the laboratory, each core was cleaned with cold water to remove drilling mud and then photographed.

In addition, HPW had seven additional boreholes drilled by a contractor using a sonic drill. Six of the boreholes were drilled and sampled to the depth of 20 m, a seventh one was drilled down to about 10 m. The samples were photographed and described on site and then were brought back to HPW facilities for grain-size and water content analyses using methodology considered proper to HPW, but not detailed in this report.

2.2.2 Permafrost sample analysis

Laboratory analyses were carried out to measure the properties of the permafrost samples. Both soil grain characteristics and ice characteristics were evaluated. To evaluate soil grain characteristics, a grain-size analysis was performed on selected samples. To evaluate ice characteristics in permafrost samples, the cryostructure, volumetric ice content and gravimetric ice content were quantified.

These methods are described below. For more information, please refer to Andersland and Ladanyi 2004.

Grain-size analysis

Sieve and hydrometer analyses of grain size were performed following a specifically modified American Standard and Testing Method protocol (ASTM D422-63, 2000). The sieves used were 4, 2, 1, 0.5, 0.25, 0.125 and 0.063 mm.

Cryostructure

Permafrost cryostructure (the geometry of the ice in the permafrost) depends on water availability, the soil's ice-segregation potential, and the time of freezing, all of which affect the development of ice structures in the soil matrix. Information such as soil genesis, climate conditions at the time of freezing, permafrost development history, and ground vulnerability when permafrost degrades can be interpreted from cryostructure (the shape of the ground ice), cryofacies (groups of cryostructures) analysis, and general cryostratigraphy (assemblages of cryofacies).

Because field descriptions are based only on a visual interpretation of the core, the samples were described a second time more thoroughly in the laboratory using standard terminology (Murton and French 1994). Frozen core samples were warmed to near 0°C and any refrozen mud was scraped off before the sample was described.

Gravimetric ice content

Ice content was calculated using:

$$u1 = \frac{(M_i\ )}{(M_s)}$$

where M_i is the ice weight, measured as weight loss after drying (g), and M_s is dry soil weight in grams. Results are expressed as percentages (dimensionless).

Volumetric ice content

The volumetric ice content was calculated by immersing the frozen sample, bagged in vacuum-sealed polybags, in a recipient to measure its volume (Vtot). The sample was then thawed and put in the oven to dry. The remaining dry material was immersed again to determinate its volume (Vsed). The volume of excess content was calculated using:

$$V_{tot} – V_{sed} = V_{ice}$$

The volumetric ice content is expressed as percentages (fundamentally meaning cm^3/cm^3).

2.2.3 Borehole logs

A log for each permafrost borehole was created by assembling laboratory photos of the cores. Borehole logs include maximal depths, grain size ratio and volumetric ice content. These logs were used as supporting data for mapping.

2.2.4 Ground temperature and climate monitoring

The three newly-drilled boreholes were instrumented to monitor ground temperature from June to October 2015. The new boreholes were all deepened using a water jet drill. The three previously investigated have been instrumented since summer and fall of 2013; data were collected from these sites and the loggers serviced.

Data from the older boreholes were logged using either a Campbell Scientific weather station, or a HOBO (U12-008) four-channel external data logger. The CR1000 station uses a programmable data logger (CR1000) attached to the sensors. In this study, the CR1000 station monitored wind speed and direction (RM YOUNG Wind Monitor); air temperature (109-L); and ground temperature (CU-BOM11012). Ground temperatures were monitored using an 11-thermistor string. This accurately records temperatures ranging from –50°C to +70°C, with interchangeability to a tolerance of +/– 0.05°C or better. The CR1000 then processed and stored the data. Measurement rates and data recording intervals are independently programmable and the program can be modified at any time to accommodate different sensor configurations or new data processing requirements. The complete set-up is powered by a ten-watt solar panel and a six-volt deep-cycle battery and is attached to a two- to three-metre adjustable galvanized steel tripod anchored to the permafrost. The battery and data logger were placed in a sealed fiberglass enclosure. The Campbell Scientific weather station was used at one site (Specifically Site 5, described below).

To monitor ground temperature at three sites (specifically Sites 2, 4, and 6, described below), a HOBO (U12-008) four-channel external data logger was used. This stand-alone weatherproof logger can record data at various intervals and uses a direct USB interface for fast data offload. The logger requires one three-volt CR-2032 lithium battery. Each battery will typically last one year when logging intervals are greater than one minute. To ensure uninterrupted operation, the data loggers were placed in a sealed 15-cm x 15-cm junction box that was connected to the borehole casing. All borehole casings were made of electrical-grade PVC filled with silicone oil. The temperature sensors (TMC6-HD to TMC50-HD) are able to accurately record temperatures ranging from –20°C to +70°C, with interchangeability to a tolerance of +/–0.25°C from 0°C to 50°C. They have a resolution of 0.03°C at 20°C.

The new boreholes at three sites (specifically, Sites 1, 3, and 4described below), were instrumented with Hobo (UX120-006M) four-channel analog data loggers; the borehole at Site 2 was upgraded with this system. Using the same type of temperature sensors (TMC6-HD to TMC50-HD), this logger notably has a superior accuracy (+/–0.15°C), and resolution (0.02°C) than the U12-008. Using two loggers per boreholes, they record temperatures at eight different depths.

In addition, ground surface temperature was monitored using the HOBO Pendant data logger (UA-002-08). This miniature waterproof two-channel data logger is able to accurately record temperatures ranging from –20°C to +70°C with interchangeability to a tolerance of +/– 0.53°C from 0°C to 50°C. The UA-002-08 loggers have a resolution of 0.14°C at 25°C.

2.2.5 Electrical Resistivity Tomography

Electrical resistivity tomography (ERT) is a geophysical method that uses stainless steel electrodes driven into the ground surface to measure the resistivity distribution of the subsurface. Resistivity is the mathematical inverse of conductivity and indicates the ability of an electrical current to pass through a material. Mineral materials (with the exception of specific substances such as metallic ores) are mostly non-conductive. Therefore, the resistivity of a soil or rock profile is governed primarily by the amount and resistivity of pore water present in the profile, and the arrangement of the pores. This makes ERT very well suited to permafrost and hydrology applications. Because most water content in frozen ground is in the solid phase, and typically has a higher resistivity than unfrozen water content, permafrost distribution can be inferred based on changes in resistivity between frozen and unfrozen ground.

An ERT system consists of an automated multi-electrode resistivity meter and a set of wires connected to an electrode array. The system used for the surveys presented in this report is an IRIS electrical resistivity system, consisting of a one-channel imaging unit and two electrode cables, each with 24 take-outs at five-metre intervals. To conduct a survey, 48 electrodes are driven into the ground along a survey line and connected to the electrode cables. A direct current electrical pulse is sent from the resistivity meter along the survey line. The resulting data consists of a cross-sectional (2D) plot of the ground's resistivity (Q.m) versus depth (m) for the length of the survey. Results of the surveys are post-treated and analyzed at the NCE using inversion software (Res2DInv 64 and Res3DInv 32).

2.3 DEVELOPMENT OF MITIGATION/REMEDIATION RECOMMENDATIONS AND PRELIMINARY DESIGNS

Based on the results of the field and laboratory analyses described above, four top-priority sites with high potential to be responsive to mitigation or remediation techniques were identified; two were discarded. The length of these sites is variable, ranging from 300 m to 1 km. These sites are targeted for the development of larger-scale test sites.

Dr. Guy Doré's team at University Laval evaluated the field, lab and geophysics interpretations provided by NCE in order to identify the most suitable mitigation and/or remediation techniques, and their most appropriate configuration, for each priority site. The design options for each site are developed with the ultimate goal of reducing permafrost instability and vulnerability to thaw. The selection of techniques is based on the combined results of technique performance from the Beaver Creek test site, published performance results from installations in other comparable areas in the North, and characteristics of permafrost at each priority site. Design options that can include one to three complementary mitigation techniques applied in combination are described for each site.

3. TECHNOLOGIES AND APPROACHES USED TO MITIGATE PERMAFROST THAW

In permafrost regions, it is essential to determine the local conditions of the site, such as climate and geologic conditions, before infrastructure is constructed or reconstructed. By contrast to warmer regions, it is important to consider the distribution of permafrost and how it will react to environmental changes, such as initial site disturbance during construction, impacts from the infrastructure itself during its life expectancy, and long term changes in climate. Mean annual air temperature, as well as any other factor which affects the thermal regime of permafrost, is important and should be considered in the site description and design.

The thermal regime is controlled by the exchange of heat and moisture between the atmosphere and the ground via their thermal properties. Table 3.1 presents a description of the factors influencing the thermal energy balance. The general climatic conditions that influence the equilibrium of the thermal regime at a place depend on its position (latitude, altitude, aspect and slope angle), since this influence the amount of incoming solar radiation and the air temperature. These climatic conditions include air temperature, wind (velocity and direction), snow depth, precipitation and solar radiation. These data can be obtained from a site-specific climate station or a nearby climate data station, and should be included in the site description. If evaluation of the above-noted climate parameters show change over time, the site description should discuss potential for two major effects: first, a general increase in the thickness of the seasonal thaw layer overlying permafrost (active layer); and second, partial or complete thaw of permafrost where ground temperature is currently close to 0 °C. Local ground surface conditions, such as surficial vegetation, snow accumulation, terrain relief and drainage condition, have a strong influence on the thermal energy balance at the interface between the atmosphere and ground.

Table 3.1. Description of site factors

Factors	Description
Climate Factors	
Solar Radiation	Solar radiation is radiant energy emitted by the sun, i.e. incoming solar energy. The amount of solar energy reaching a specific surface unit is influenced by latitude, altitude, aspect and slope angle. Radiation increases with increased altitude and decreases with increased latitude. When reaching the ground surface, shortwave solar radiation will either be reflected, or be transformed into longwave radiation (heat) and then absorbed into the active layer and permafrost. The amount of solar radiation transformed into heat will depend on the conductivity of each component of the ground, and the albedo of the surface. Albedo is the fraction of solar energy (shortwave radiation) which is reflected by the surface. Dark material, such as organic soil, has a low albedo, meaning that it absorbs the solar radiation as heat; while light-colored material, such as snow, has a high albedo, meaning that it reflects most solar radiation.
Wind	Wind affects the snow distribution and provides convective cooling or warming influence depending on the temperature of the wind. Wind is primarily a serviceability concern because it can impact road safety and maintenance due to white-outs, snow drifts and wind-swept debris.
Precipitation	Water can be a source of heat at the surface. It can cause conductive transfer (accumulation) and in the ground and embankment, by convective transfer (water flow). It also contributes to latent heat exchange in the embankment and ground during phase change processes (water/ice).
Snow Cover	Snow can insulate the ground surface from winter cold air temperature and limits heat extraction. Depth and density of snow will influence the ground surface temperature, with deeper, low density snow being more likely to have a warm subnivean layer. The type of snow cover depends on site characteristics, such as micro relief, vegetation, prevailing wind, and embankment geometry.

Table 3.1. Description of site factors (Cont.)

Surface Characteristics	
Embankment slope and orientation	Embankment slope and orientation are influential on the amount of energy that the ground surface receives from the sun. In mountainous areas, it is not uncommon to have permafrost in north-facing slopes and no permafrost in south-facing slopes. Also, there may be localized accumulation due to snow drifting.
Vegetation Cover	The primary effect of low vegetation such as mosses and shrubs is to shield permafrost from solar radiation during summer months. In addition, trees are also important regulators in permafrost regions because they reduce exposure to solar radiation intercept snowfall in winter. Surficial vegetation can be altered by human activities such as construction of transportation infrastructure and by natural events such as fire and precipitation changes. Any removal, damage or compaction of surficial vegetation can alter the thermal energy balance.
Drainage	Drainage is very important to consider even though precipitation is generally low in many cold permafrost regions. Permafrost can be affected by standing or flowing water due to its heat storage capacity and erosion. The movement of surface and subsurface water can have a significant effect on the stability of a field site. However, the impact of water flow is often difficult to predict. In discontinuous permafrost regions, drainage conditions are usually linked to vegetation, snow cover and other terrain factors. Drainage can have an adverse impact on the thermal stability of permafrost, and infrastructure is likely to influence that interaction.
Subsurface conditions	
Soil Types	Adverse conditions, such as high ice content, poor drainage conditions and frost susceptibility, are usually associated with fine-grained and organic soils. Transportation infrastructure problems, such as differential settlement and frost heaving, tend to occur in poorly drained, fine-grained soils with high ice content. Fundamental properties of soils determine the penetration depth of freezing and thawing given temperature differentials over a given period of time for non-permafrost and permafrost conditions, respectively.
Ground Ice Conditions	The type and the quantity of ice present in the top part of permafrost reflects permafrost growth conditions and is a major factor in assessing the risk related to permafrost degradation. The higher the content of ice in excess of the soil natural porosity, the higher the risk of instability during the degradation of permafrost.
Ground Temperature	Major factor controlling the stability of permafrost and determining the need for mitigation or adaptation construction techniques.

Detailed information, including air temperature, ground temperature (mean annual ground temperature and annual variation), wind conditions (direction and velocity), precipitation, solar radiation, surficial vegetation, snow cover, topography (small and large scale), aspect, soil types, ice type, volumetric ice content, drainage, climate warming, and surficial geology should be used to characterize a site. However, the level of detail required for a site description depends on types of analysis desired for a given construction or rehabilitation project.

3.1 MITIGATION TECHNIQUES

To protect an embankment in permafrost regions, several mitigation techniques are proposed for consideration. All have been tested on field sites and shown to mitigate either the thaw of permafrost or the effects of permafrost degradation (Goering, 1998; Zarling, 1984). These mitigation methods can be classified into four categories:

1. Preventing heat absorption into the permafrost underneath the embankment;
2. Extracting heat to prevent additional heat absorption underneath the embankment;
3. Reinforcing the embankment, using geogrids and geotextiles; and,
4. Other methods, such as pre-thawing, snow removal, and subsurface permafrost excavation and replacement.

The embankment thickening technique is based on increasing the thermal resistance to protect the underlying permafrost. However, this method cannot compensate for the effects of climate warming. For the other mitigation techniques, there are different thermal effects from “active cooling” to “passive cooling”, as shown in Figure 3.1.. Active heat extraction methods include thermosyphons, air convection embankments (ACE), air ducts and heat drains (HD). These approaches provide the ability to actively remove heat from the embankment. Passive mitigation methods preventing heat absorption include reflective surfaces, insulation and embankment thickening. These methods prevent heat from entering the embankment and do not actively remove heat from the system (Ferrel and Pasi, 2010). Methods such as snow/sun sheds may be included in both categories as they facilitate ground cooling during winter by preventing snow accumulation and allow air circulation between the embankment and the shed, and also prevent solar radiation from reaching the surface year round.

Methods in categories (3) and (4) are mainly used to ensure and enhance the mechanical stability, and are used before and after the construction of transportation infrastructures. These methods are not widely applied in permafrost regions.

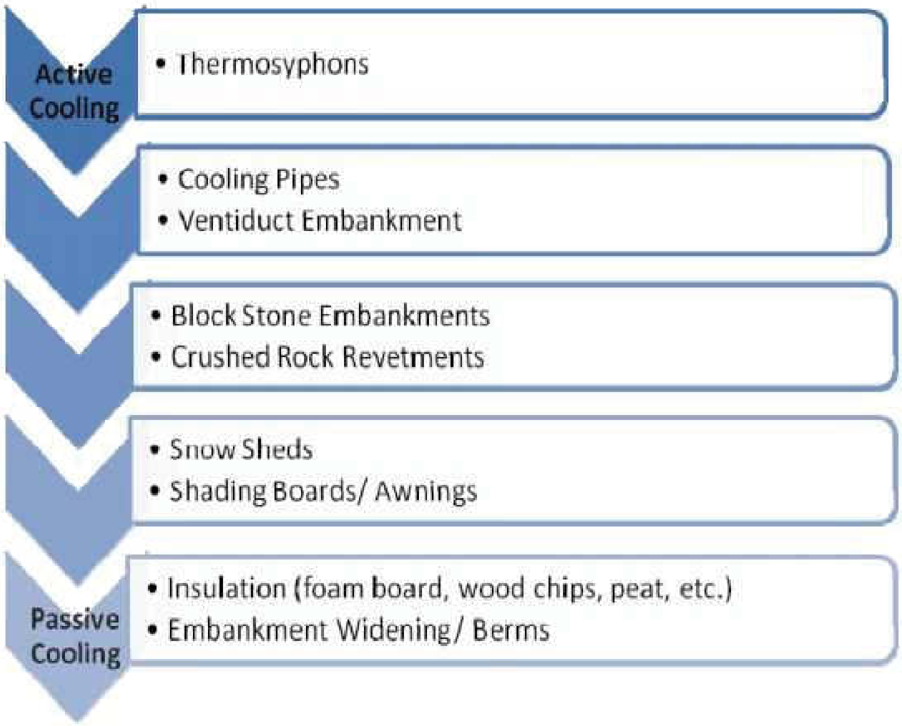


Figure 3.1. Active cooling vs. Passive cooling (Ferrel and Pasi, 2010)

Since trends in climate are already evident in northern Canada and expected to increase, the embankment thickening mitigation technique will not be considered for this adaptation project in Yukon. As a result, this project considers thaw mitigation techniques including air convection embankments, heat drains, air ducts with chimneys, thermosyphons, insulation, and high albedo surfaces.

3.2.1 Air convection embankment

Air convection embankments use a highly porous, poorly graded material like boulders or cobbles with a low fine content, to construct significant portions of the embankment. During winter, cold temperatures cool the surface and upper portion of the embankment, while the temperature at the base remains relatively warm due to heat accumulation in the ground during summer. The temperature difference between surface and the base results in an unstable air density gradient, which is balanced by air circulation in the pore space between the grains. This method enhances winter heat transfer in a porous embankment with sufficient air permeability. During summer, the embankment air density gradients are stable and air circulation will not occur. Due to the low thermal conductivity of air and relative small contact area of the stones, the rock layer begins to function as a thermal insulation barrier, which results in heat loss in winter and limited heat transfer in summer (Goring, 2002). It is a promising technique, and requires competent rock and the capacity to produce specific material near the site.

Theoretically, an ACE cooling system can be regarded as a horizontal layer of porous material that will experience natural convection (Figure 3.2), and the natural convection can happen if Rayleigh Number *Ra* is larger than critical Rayleigh Number Ra_c ($4\pi^2 \approx 39.5$). The Rayleigh Number is defined as:

$$Ra = \frac{C\beta gKH\Delta T}{\nu k} \qquad (1)$$

Where $C =$ volumetric heat capacity of the pore fluid (air, $J/m^3 \cdot K^{-1}$), β = expansion coefficient of the pore fluid (air, K^{-1}), g = acceleration of gravity (m/s^2), ΔT = temperature difference between the top and bottom surface, $K =$ the intrinsic permeability of material, $H =$ height of layer, $\nu =$ kinematic viscosity of the fluid (air, m^2/s), and $k =$thermal conductivity of the material (W/m·k).

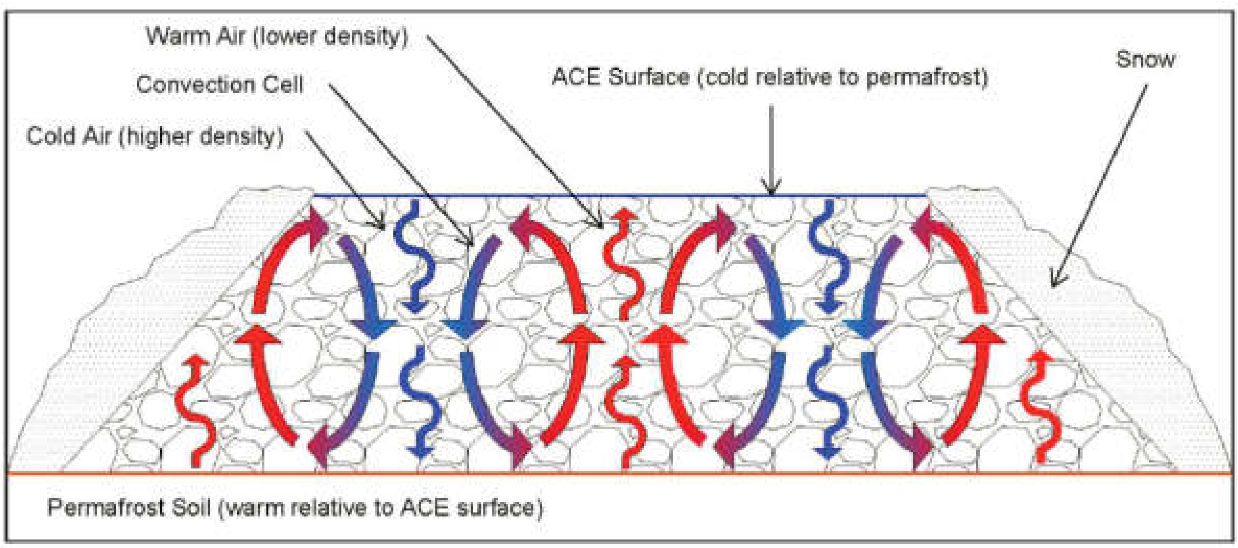


Figure 3.2. Pattern of winter-time pore air circulation (Jensen, 2015)

Using the critical Raleigh number, a critical ΔT is defined as follows:

$$\Delta T_c = \frac{40\nu k}{C\beta gKH} \qquad (2)$$

Once the critical ΔT is exceeded, natural convection will occur.

Several types of air convection embankments have been developed to cool down the foundation of transportation infrastructure (Figure 3.3). For an interlayer ACE, the total thickness of the embankment should be at least 2.5 m, and the thickness of the overlying sand and gravel directly affects the amount of cooling. The protective berm and revetment configurations cool the side slopes of the embankment. A U-shaped ACE combines all the benefits of each ACE configuration, and has the advantage of cooling the center and the sides of the embankment. This configuration may have the best cooling performance.

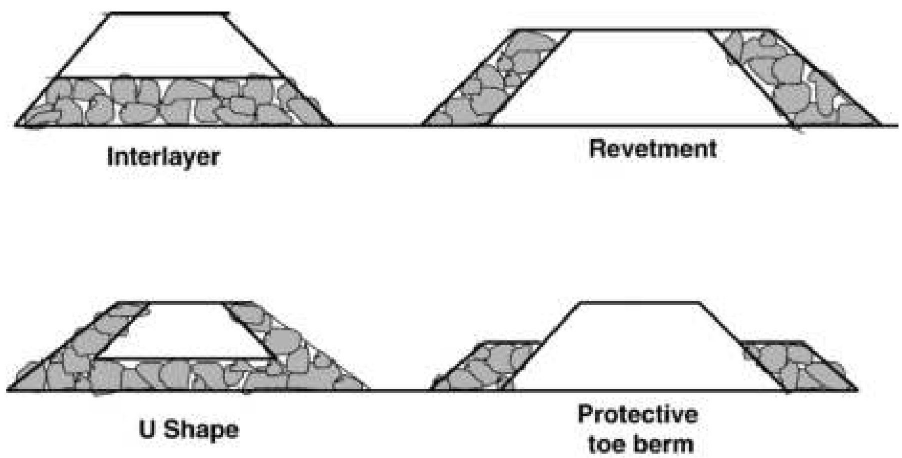


Figure 3.3. Various ACE embankment configurations

3.1.2 Heat drain

Heat drain is an innovative mitigation technique that was proposed by the Pavement Engineering Research Group at Université Laval in the early 2000s. It consists of a thin air layer (25 mm) of a flexible drainage geocomposite (Figure 3.4). HD is lightweight and can be easily installed and transported to field sites. HD can be placed in the shoulder of the embankment, underneath the embankment or on the slopes of embankment, depending on where cooling is required. When stones are not available near the construction site, HD is a promising solution to protect the whole embankment or part of it. Two controllable factors impact the performance of heat drains:

- Stack height - From above equation, a taller stack will increase the chimney effect pressure difference resulting in greater air-flow. However, the stack height is also a safety consideration.
- Smoothness of air duct - The air speed can increase with smoothness of air duct surfaces.

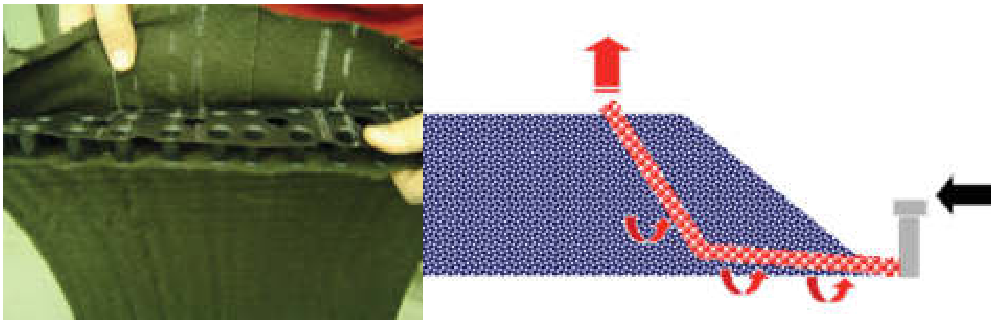


Figure 3.4. Heat drain (from Jorgensen et coll., 2008)

3.1.3 High albedo surface

A HAS is a passive mitigation method, which is based on reducing heat intake on the surface of embankment. A HAS is typically created by coating the road surface with a high albedo treatment. Albedo is defined as the ratio between reflected and the incident solar radiation, which is expressed as:

$$a = \frac{I_R}{I_I} \quad (3)$$

where $a =$ albedo, I_R = reflected solar radiation, and I_I = incident solar radiation. It is expressed as a fraction ranging between 0 (perfectly absorbing) and 1 (perfectly reflecting). Weaknesses of HAS include costs of initial coating application, possible high level of maintenance and associated maintenance costs due to frequent recoating and potential for decreased traction. To overcome these, it is necessary to respect the technical specifications for coating products to be used in northern regions. A light-colored aggregate used in bituminous surface treatment (BST) is another approach for HAS.

3.1.4 Insulation

The use of plastic insulation beneath pavement was first investigated in the early 1960’s. Thermal insulation is a passive method to protect permafrost, which is achieved by increasing thermal resistance. Although insulation may not stop the rise in the mean annual ground temperature and the deepening of the permafrost table, it may delay or stabilize permafrost degradation.

The effectiveness of insulation layers depend on the relationship between the soil to be protected and the environmental conditions. In winter, permafrost is warmer than the atmosphere, and the thermal insulator has the effect of “heat preservation”, which can decrease the heat extraction. In summer, thermal insulation acts as “cold preservation”, which can reduce heat absorption. It is more effective if used in combination with heat extraction methods, such as ACE, HD and air duct systems.

Polystyrene insulation is one of the most frequently used techniques for thermal insulation of embankments, and it can be susceptible to mechanical damage. Vehicle traffic and the overlying soils can compress or fracture the insulation board, reducing its effectiveness. When polystyrene insulation is used in the design, positioning and installation methods should be carefully considered.

3.1.5 Thermosyphons

Thermosyphons are an active thaw mitigation method to remove heat from the soil and decrease the subsurface temperature in permafrost regions, and it is most suitable for severe localized problems. Typically, thermosyphons consist of a sealed, fluid filled tube with an upper part above the ground working as a condenser and a buried part in the ground functioning as an evaporator. Most condensers have fins to create a better surface area available for cooling. The most commonly used working fluid is carbon dioxide (CO_2). Ammonia and butane are also used. The advantage of CO_2 thermosyphons are that they have low maintenance costs, no operating cost, and are environmental friendly.

To trigger heat transfer, a temperature difference of at least 1 °C between the condenser (air) and the evaporator (underground) is needed. Heat transferred from the ground expose the fluid contained in the evaporator to warmer temperature. The liquid evaporates and vapor rises along the pipe. When the vaporized fluid reaches the condenser and is exposed to colder air (outside), condensation takes place. The condensed fluid is then pulled down to the evaporator by gravity and the cycle is repeated. Whenever air temperature is warmer than the soil temperature, the cycle stops.

3.2 SYNTHESIS OF INFORMATION ON MITIGATION TECHNIQUES

This section presents and compares the requirements, specifications and considerations related to the mitigations techniques relevant to the sites selected in this project. Table 3.2 presents the cost, the maintenance and the permafrost conditions required to apply those techniques. The effectiveness, height requirement, implementation and strength/durability considerations related to mitigation techniques are also presented in Table 3.3.

Table 3.2 Permafrost conditions, cost and maintenance

Mitigation Techniques	Ice Content	Temperature	Cost of Construction	Maintenance
ACE	Ice-rich	Warm permafrost or slightly below -2 °C	Moderate	Low
HD			Moderate	Low
HAS			Low	High
Thermosyphons			High	Moderate
Insulation			Low	High

Table 3.3: Effectiveness, installation requirement, implementation and strength/durability considerations

Mitigation Techniques	Effectiveness (based on literature)	Height/Depth Requirement	Implementation Consideration	Strength / Durability Considerations
ACE	Depends on the design. Rising mean annual ground temperature generates more cooling. Measurable rise of permafrost table and decrease of embankment temperature. Less severe settlements and stabilization over time.	Minimum height of embankment 2.5m	Uncovered ACE is sensitive to intrusion by fine soilsa. Local availability of suitable aggregates may be problematic. Orientation of embankment with respect to intensity of solar radiation and wind direction should be considered when designing ACE.	The high strength of the stones makes it suitable for many conditions such as heavy loads and it also provides very low maintenance. If settlement happens, it will lose efficiency but will keep working.
HD	Measurable rise of permafrost table and decrease of embankment temperature.	Minimum height of embankment 2.0m 2.0 m	Labour-intensive (manual installation). Avoid installation during windy day. Need to carefully follow the design.	During installation, a layer of sand must carefully be placed on HD for protection. Must avoid puncture or compression by heavy equipment.
HAS	Measurable decrease of surface temperature.	No specific embankment height requirement	Availability of light-colored aggregate may be problematic. High albedo coatings need to respect specification for northern use.	Durability has a close relationship with the material quality.
Thermo--syphons	Measurable rise of permafrost table and decrease of embankment temperature.	No specific embankment height requirement	Angle of inclination, spacing and length must be adjusted to the site conditions. Susceptible to damage and vandalism.	If a puncture of the tube occurs, the pressurization is lost and the tube will no longer function correctly.
Insulation	Promote thermal stability and delays thawing. May not reverse warming trend.	Depth of insulation varies from 0.5 m above natural ground surface to 0.8 m below the embankment surface (Zhi, et al., 2005).	Avoid trapping heat in the ground under the insulation layer by implementing in winter/early spring. Relatively easy to construct. Insulation properties may be reduced by the potential for water absorption and compression or breaking of the material. Insulation layer thickness, width, and embedded depth must be adjusted to site conditions.	Sensitive to mechanical damage. Insulation material has to be installed deep enough to prevent crushing from cyclic wheel loadings and to reduce the risk of differential icing at the surface of the pavement.

4. ADAPTATION SITES

Permafrost thaw mitigation techniques are applicable in conditions where permafrost is relatively thick, ice-rich and reasonably cold. The expected long-term poor performance of road embankments in those conditions increases the likelihood of protection techniques to be cost-effective over the design life of the infrastructure. Because this project is focussed on piloting thaw mitigation techniques for Alaska Highway prior to deploying the techniques along larger sections of the highway, the following criteria were sought for the sections investigated in this project:

- **$T_{permafrost} < -1$ C:** This temperature threshold will minimize the amount of unfrozen water in permafrost, thereby reducing the amount of latent heat to extract and facilitating thermal stabilization.
- **Permafrost thickness ≥ 10 m and volumetric ice content ≥ 40%:** Thick, ice-rich permafrost leads to poor embankment performance over a long period, thus justifying the use of a protection technique**.** While fine grained soil have higher moisture content and often proved to content significant amount of excess ice, some coarse grained sites can also be ice rich as shown by the Dry Creek site. Consequently, the characterization focuses on verified ice content rather than soil texture.
- **Sections without lateral flow of water or thermokarst:** This criterion is intended to minimize convective heat transfer to permafrost underneath the embankment, which would reduce or even eliminate the effectiveness of the protection technique.
- **Uniform section over the protected area:** This involves uniformity of soil conditions and embankment geometry. It is intended to reduce interpretation problems related to variable conditions along the protected section.
- **Sections without important curves or slopes:** This criterion is intended to limit the safety impacts or other problems, which could occur following the implementation of a protection technique. For example, the use of high albedo surfacing materials can cause localized icing, which can be hazardous in curves or sloped areas.
- **Ideally in an area where geotechnical borehole, ground temperature and geophysical information is available:** This would facilitate the analysis and modelling by providing additional reliable information on soil conditions and information along a cross section if geophysical information is available.

4.1. ADAPTATION SITE 1: KOIDERN NO. 2, KM 1809

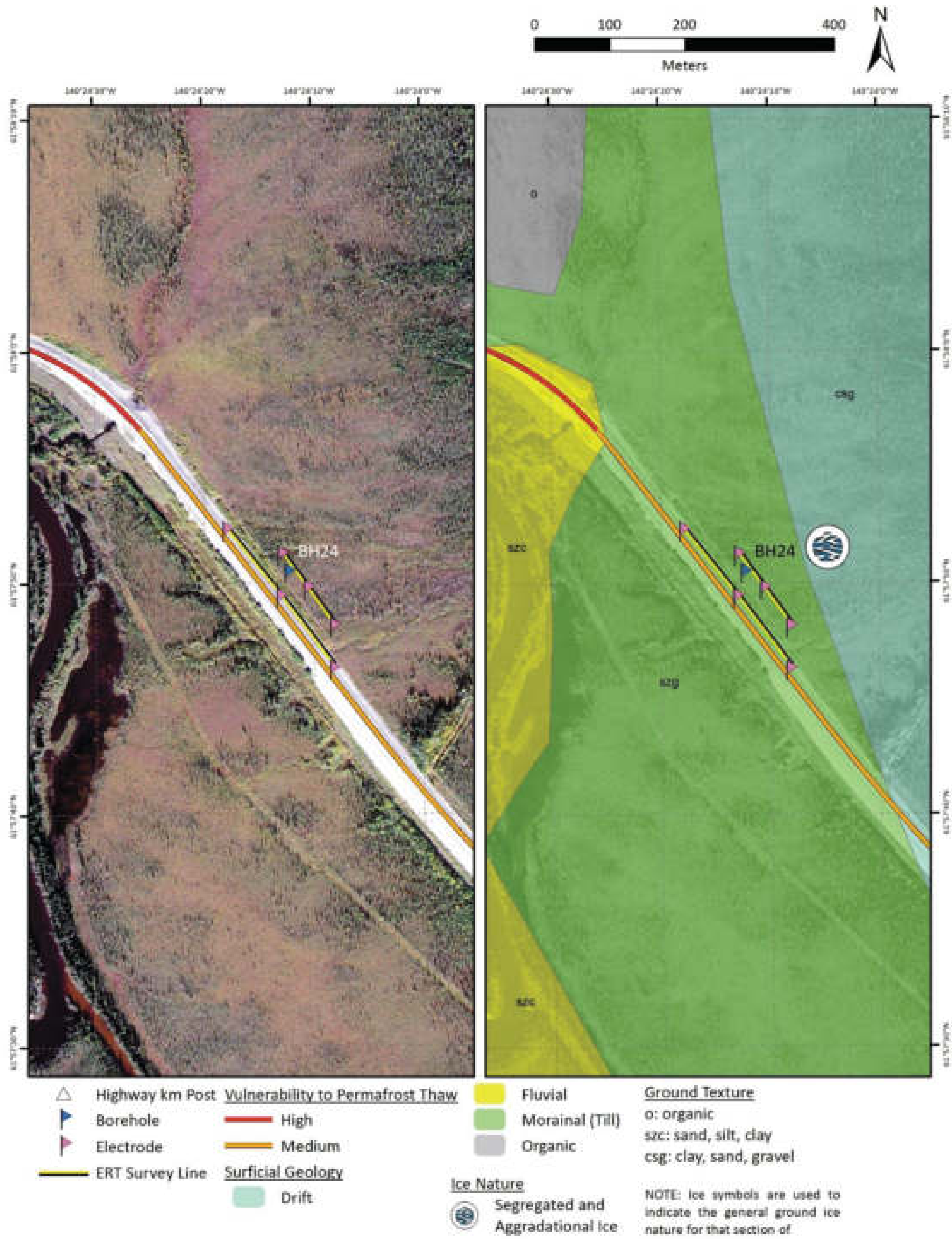


Figure 4.1.1. Vulnerability maps of Site 1 (satellite imagery and surficial geology)

4.1.1 SURFICIAL GEOLOGY AND PERMAFROST CHARACTERISATION

- This highway section is underlain by relatively resilient permafrost (-1.6°C).
- The section crosses morainic units that have medium vulnerability to thaw due to the low to moderate ground ice content in these units, massive ice has been observed close to the surface.

4.1.1.1 Geology

When facing north, this section of the road crosses over morainic surficial deposits and is bordered by a fluvial unit to the left and a drift deposit to the right (Figure 4.1.1). Both the morainic and drift units are made of heterogeneous sediment (coarse material in a finer matrix) that can be overlain by colluvium and slope deposits at the foot of the hill slopes. The fluvial sediment ranges from silt to gravel.

A meandering river system passes through the fluvial unit at a distance ranging from 150 to 500 meters of the section under consideration. The river has deposited relict meanders and fine-sediment deposits. Permafrost developed (aggraded) in these fine deposits during a colder period, forming a significant amount of ground ice. Because of warming temperatures, thermokarst features are now developing.

The morainic unit is comprised of coarse sediment that is less favourable to the development of ground ice, and therefore less thaw-sensitive. In addition, permafrost developed epigenetically after the glaciers retreated, from the top to the bottom, which has constrained its thickness.

The drift deposits have a higher content of fine grained sediment.

4.1.1.2 Permafrost

Two boreholes were drilled along this section: one was drilled by the NCE in the field, and one was drilled by a contractor for HPW at the toe of the road embankment (not shown on the map). The NCE borehole log is shown in Figure 4.1.2. The first 2.02 m consist of ice-rich silty sand and sandy silt; massive ice is found from 2.02 m to 2.66 m (the end of the borehole). In order to monitor ground temperature, the borehole was deepened down to 5.75 m using a waterjet drill. The extent of the massive ice remains unknown, but based on the water jet drilling should not exceed the final depth of the borehole. A log of the HPW borehole is presented in Figure 4.1.3 and photos of the core are in Figure 4.1.4. Noticeable features include an ice and organic silt layer reported from 1.6 to 4.6 m, and bedrock that is reported starting at 7.5 m. Combined, the two borehole indicate an ice-rich to pure ice layer of about 3 to 3.5 m thickness.

Two ERT surveys were conducted on this section (Figure 4.1.5). Using the borehole logs as reference, the ERT survey in the field suggests the presence of ice-rich permafrost at between 2.5 to 8 m depth. Permafrost can be expected to be as thick as 10 to 12 m, until contact with the bedrock, and possibly beyond. The ERT survey done along the toe of the embankment shows a contact with bedrock. This is consistent with the HPW borehole log. At several of the ERT surveys performed along the road embankment in May 2015, the results have to be considered with caution as rain and general humidity caused the system to underperform.

Figure 4.1.6 and Table 4.1.1 show ground temperatures recorded from June to October 2015 in BH24. During this period, the deepest (5.75 m) ground temperature ranged between -1.6 and -1.9°C. The temperatures are warm but well below 0°C.

Table 4.1.1. Ground temperature recorded at BH24

	0 m	0.5m	3m	5.75m
2015				
June (from 8th)	16.6°C	0.6°C	-1.2°C	-1.6°C
July	15.2°C	2.5°C	-1.5°C	-1.9°C
August	10.7°C	2.9°C	-1.2°C	-1.8°C
September	5.4°C	1.3°C	-1.1°C	-1.7°C
October (until 13th)	-0.6°C	0.2°C	-1.0°C	-1.6°C

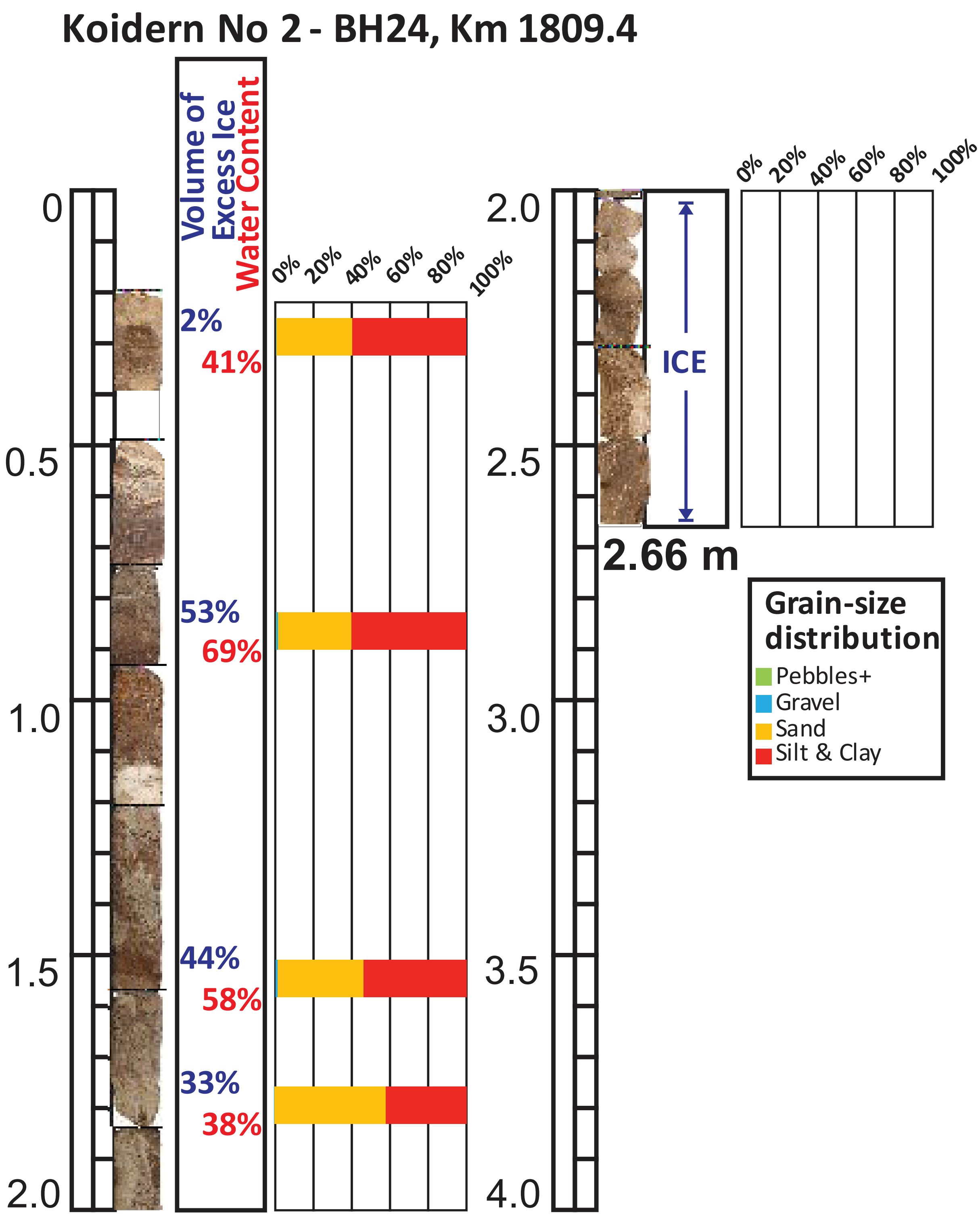


Figure 4.1.2. Log of borehole BH24.

SUBSURFACE EXPLORATION AND TEST REPORT	**Alaska Highway - Site 1 - Koidern No 2 area**	SOURCE/TP#: **866-5312**
Boart Longyear	Establishment of Baseline Data, km 1810 RHS	PROJECT NO: 552-202021-0601-05-1
Sonic Drill	Coordinates: Z Nm Em	ELEVATION: m

SAMPLE TYPE: UNDISTURBED, DCPT, AUGER, BULK, SPT, CORE

SOIL DESCRIPTION	Depth (m)
PEAT -Dark brown, fiberous, saturated	
ORGANIC SILT -Dark brown, Nbe	1
ICE and ORGANIC SILT -50% Vr, Clear, white, fractured -Dark brown Silt -Vx	2 3 4
SILTY SAND -Dark brown, rounded -Vr, clear, white SILTY SAND with GRAVEL -Highly fractured gravel -Angular, grey, oxidization evident	5 6 7
BEDROCK -Pulverized in drilling -Grey	8 9
END of HOLE	

Yukon Highways and Public Works Transportation Engineering Branch	LOGGED BY: R.Stilwell	Termination Depth: 9.1m
	COMPILED BY: R.Stilwell	Complete: 9/13/2015
	REVIEWED BY:	Pit #: Page 1 of 1

Figure 4.1.3. Log of borehole 866-5312

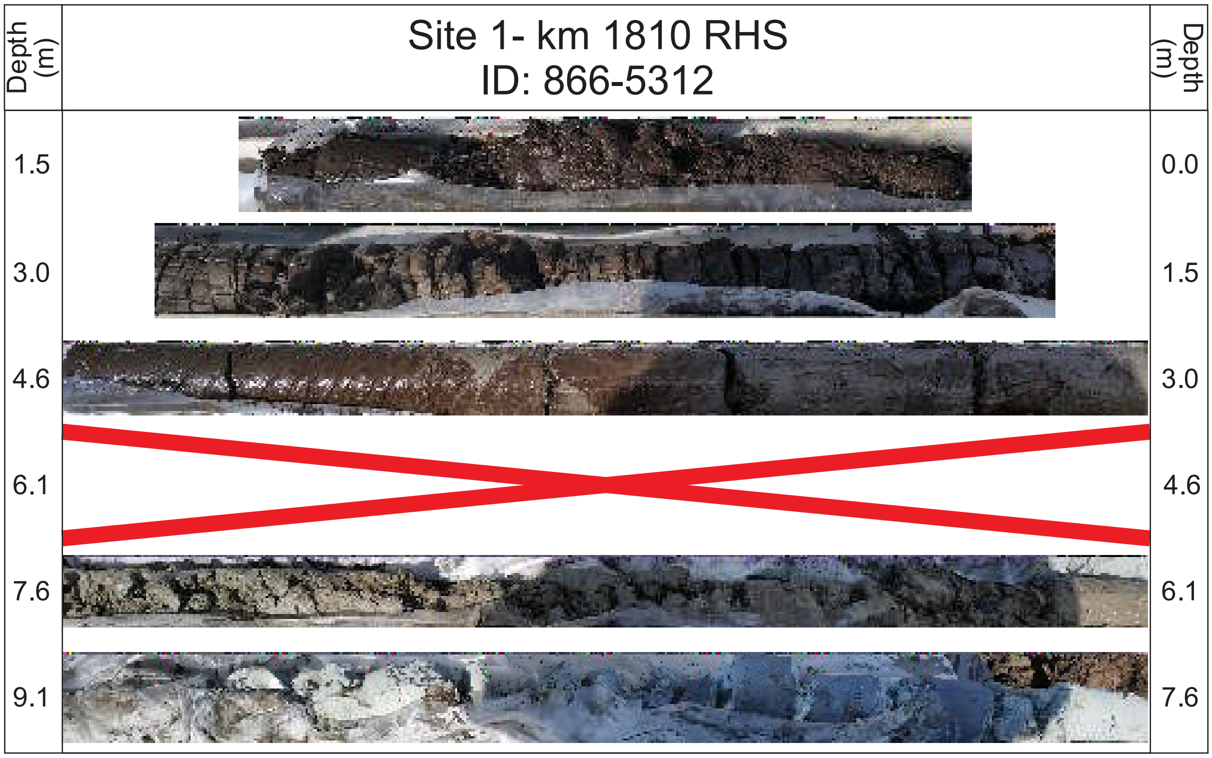


Figure 4.1.4. Cores collected from borehole 866-5312

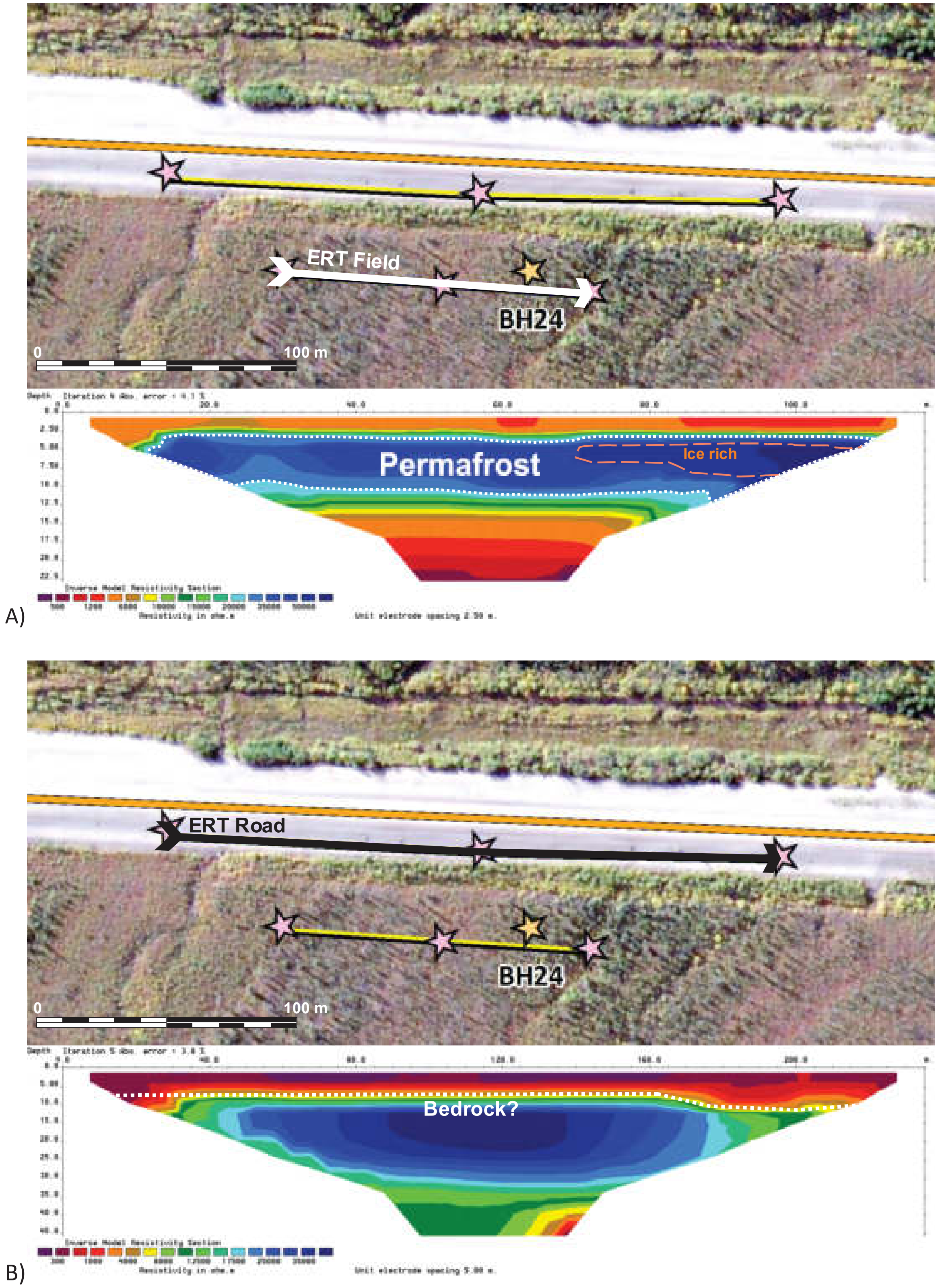
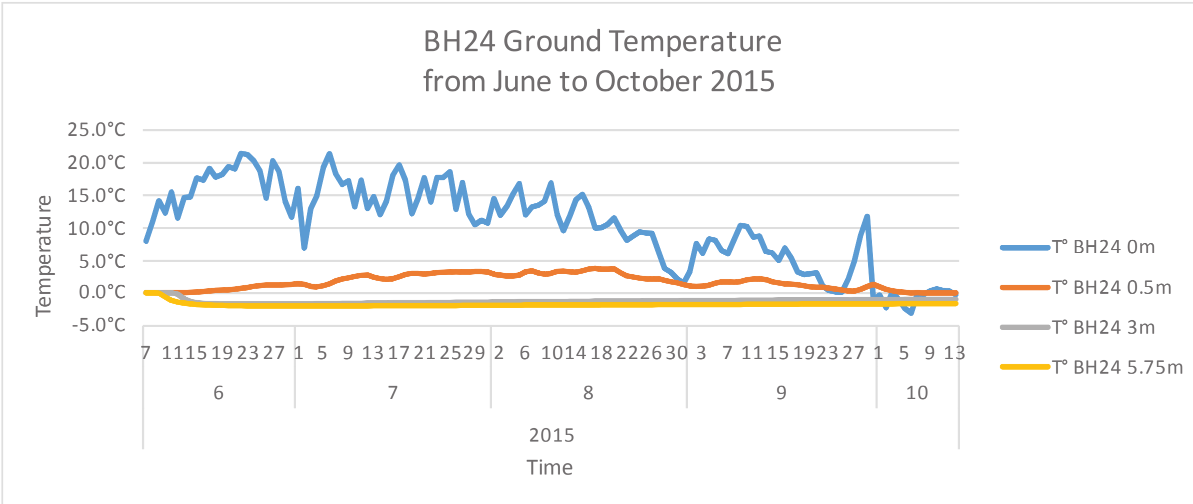


Figure 4.1.5. ERT Surveys performed at Koidern No 2 site for A) in the field; and B) along the embankment.



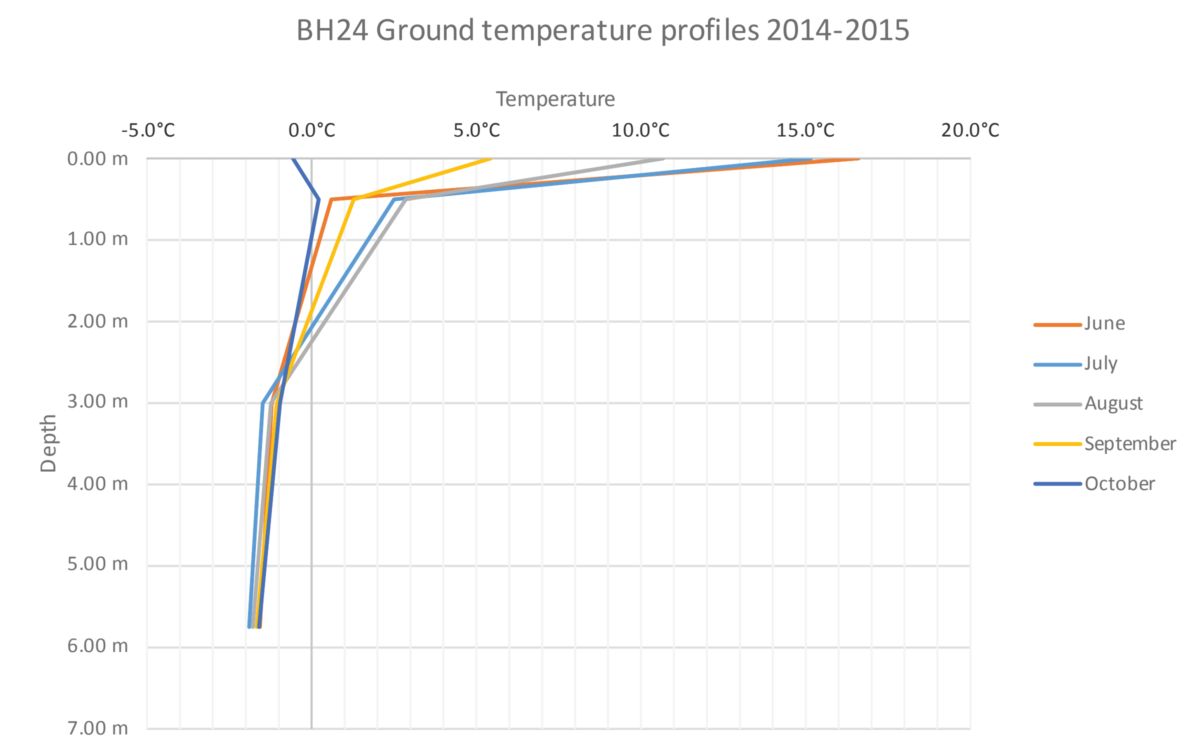
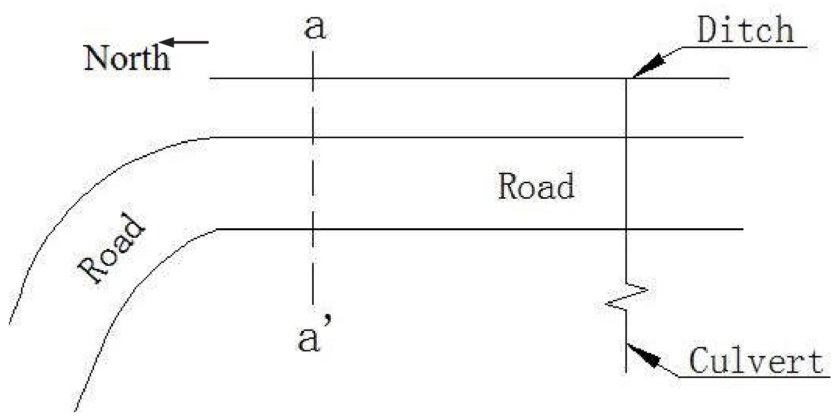


Figure 4.1.6. Ground temperature recorded in BH24 from June to October 2015.

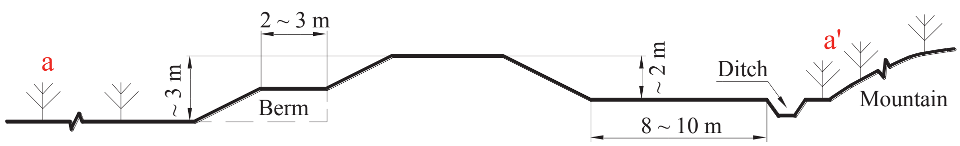
4.1.2. Adaptation design

4.1.2.1. Site configuration

The proposed embankment cross section is located at km 1809.5 (Figure 4.1.7). A forested hill covered with a high-density forest is located along the east side of the road (right hand side looking north). No water ponding was observed during field visits although a few creeks flow from the foot of hills and are collected by an interceptor ditch leading to culverts.



A)



B)

Figure 4.1.7. Schematic illustration of the Koidern No.2 adaptation site A) Localisation of proposed embankment cross section in transverse profile; and B) a-a' embankment cross section, km 1809.5

A 2-m wide, 0.5-m deep interceptor ditch has been dug on the right side (looking north) of the road, about 10 m away from the toe of the embankment, and a mountain slope is above the ditch. Spring runoff and summer precipitation tends to flow down this slope.

The black topsoil on the right side of embankment was laid in September 2015 using the material removed from the ditch (Figure 4.1.8.). While this topsoil will increase heat intake in the ground at the toe of the embankment during the few first years, vegetation cover will develop and progressively contribute to ground cooling along the embankment.

A) 

B) 

Figure 4.1.8. Koidern No. 2 adaptation site, km 1810.2 for A) Left and right sides of the embankment, facing north; B) Right side of the embankment, facing south.

The vegetation cover on both sides of embankment is comprised of trees, shrubs and other plants (Figure 4.1.8). Specifically, on the left side of the road (when facing north), high-density vegetation is distributed (about 90% of land covered) about 4 m from the toe of embankment. On the right side (when facing north), there is no vegetation on the newly laid black topsoil. However, a high-density forest is present beyond the ditch. The density of trees on the right side of the embankment significantly decreases at higher elevation on the side of the hill, with only about 5% of land covered at the top.

4.1.2.2. Site thaw-sensitivity

The borehole data and ERT survey both show ice-rich soil that extends to +10 m below ground surface. Thick massive ice has been reported by HPW and also indentified in a NCE borehole located in the field.

Ground temperature is about -1.6°C; warm enough to make the permafrost sensitive to air temperature increase. Due to climate change, based on General Circulation Models (GCMs), temperature increases of 1.5-2.5°C for 2030s and 2.5-4°C for 2050s are expected. Moreover, precipitation increases are also expected in the range of 20-50 mm for 2030s and 30-80 mm for 2050s. With the current ground temperature, and high excess ice content, the permafrost can be described as highly thaw-sensitive, and therefore, the embankment is vulnerable to degradation.

The detailed information about Site 1 is summarized in Table .

Table 4.1.2. Summary information for adaptation Site 1

Permafrost distribution (ice-rich)	**Mean Annual Ground Temperature (°C)**	**Height Difference (m)**	
		Right Hand Side	**Left Hand Side**
8 m ~ more than 10 m	-1.6*	2.0	3.0
Excess ice content (Maximum)	**Soil Types**	**Climate Warming (°C)**	
		2030s	**2050s**
59% to massive ice	Mainly fine-grained	1.5 to 2.5	2.5 to 4.0
Vegetation (Land Cover)	**Surficial Material**	**Drainage Condition**	
About 90%	Glacial (moraine)	Interceptor Ditch	

* Mean annual ground temperature is estimated based on less than a full year of data.

4.1.2.3 Adaptation suitability

While the ground temperature is relatively warm, it remains below -1°C. Permafrost is ice-rich (excess ice content>40%) down to approximately 8 m on the right had side of the embankment, and its thickness may exceed 10 m if it propagates into the bedrock. The overall depth of permafrost is not crucial information because the bedrock is not thaw sensitive. These conditions make it vulnerable to temperature increases as thaw will trigger thermokarst. Protection measures should be implemented at both sides of the embankment rather than only one side, as failures, notably those induced by settlement, may happen on either side following climate warming or ground surface disturbances such as vegetation removal. The lateral flow of water along the embankment is controlled by the interceptor ditch and culverts. Site 1 is a relatively uniform section of highway without curves or slopes. Therefore, Site 1 is a good candidate for adaptation.

4.1.2.4 Adaptation strategy

Black, organic rich soil has been spread along the embankment. Once vegetation has developed on the black soil, it will favor heat extraction through shading and evapotranspiration. Reconstruction of the road required to apply mitigation techniques will likely induce a thermal disturbance, especially if work takes place in summer. Summer work will result in more heat flow and an increase of permafrost temperature.

To protect permafrost and the overlying road, the mitigation method shall be aggressive to decrease permafrost temperature as soon as possible, and not just compensate the expected climate warming and/or control thawing rate. Active methods based on natural convection, have more effective abilities to extract heat from the foundation of transportation infrastructures. Active mitigation techniques such as ACE, HD and air duct with chimney, should be considered for application on this site.

To maximize the effectiveness of thermal stabilization, a combination of mitigations techniques should be considered. For example, a high albedo surface that will limit heat intake can be used in combination with convective heat extraction techniques installed in the embankment shoulders.

Based on considerations described in section 3.2, the required embankment height for most convective systems is 2.5 m. The embankment heights estimated during site visit are 2.0 m on the right side and 3.0 m on the left side. A slight increase in embankment height would be beneficial if the site is selected and the use of convective systems is considered.

Based on considerations described in section 3.2 and site conditions, the proposed mitigation techniques are the following:

1. ACE (U shape Figure 4.1.9)
2. ACE placed on shoulder with HAS (Figure 4.1.10)
3. HD with HAS (Figure 4.1.11)

The adapted section extends from km 1808.6 to 1809.6 for a length of 1000 m.

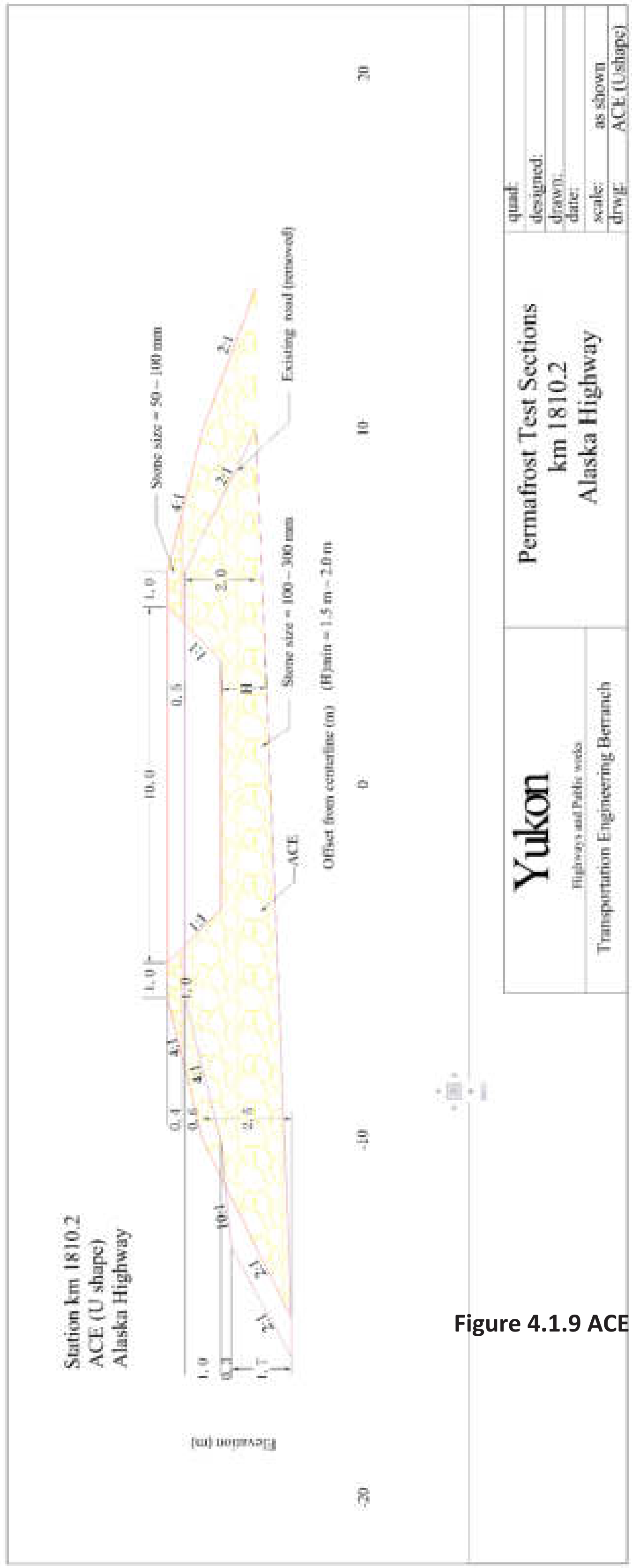


Figure 4.1.9 ACE (U shape)

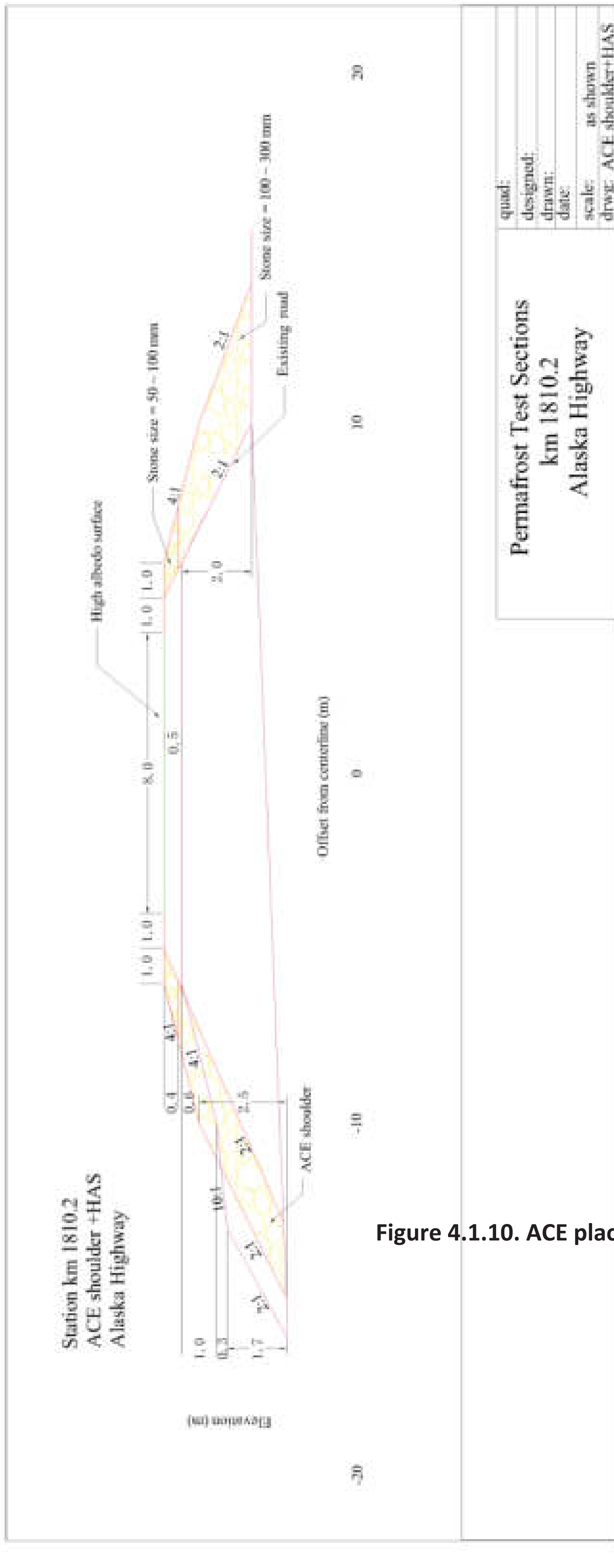


Figure 4.1.10. ACE placed on shoulder with HAS

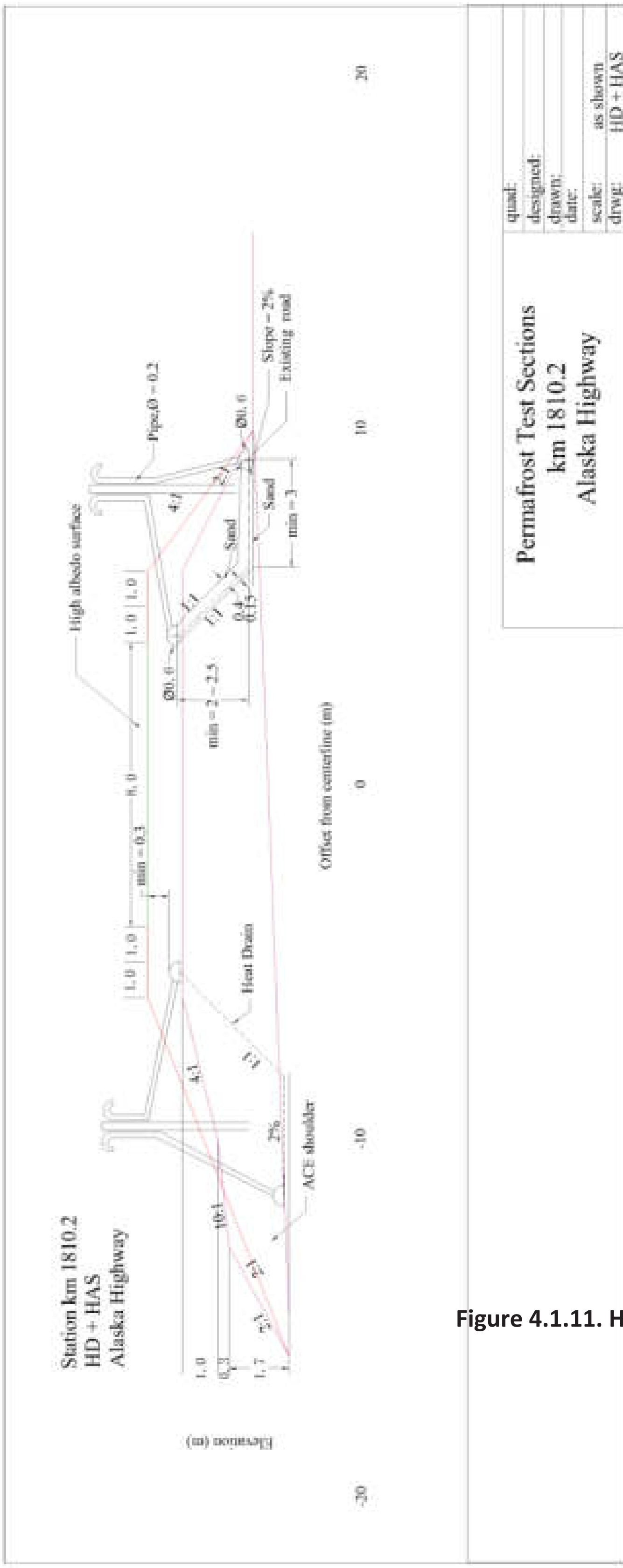


Figure 4.1.11. HD with HAS

ADAPTATION SITE 2: DRY CREEK, KM 1840

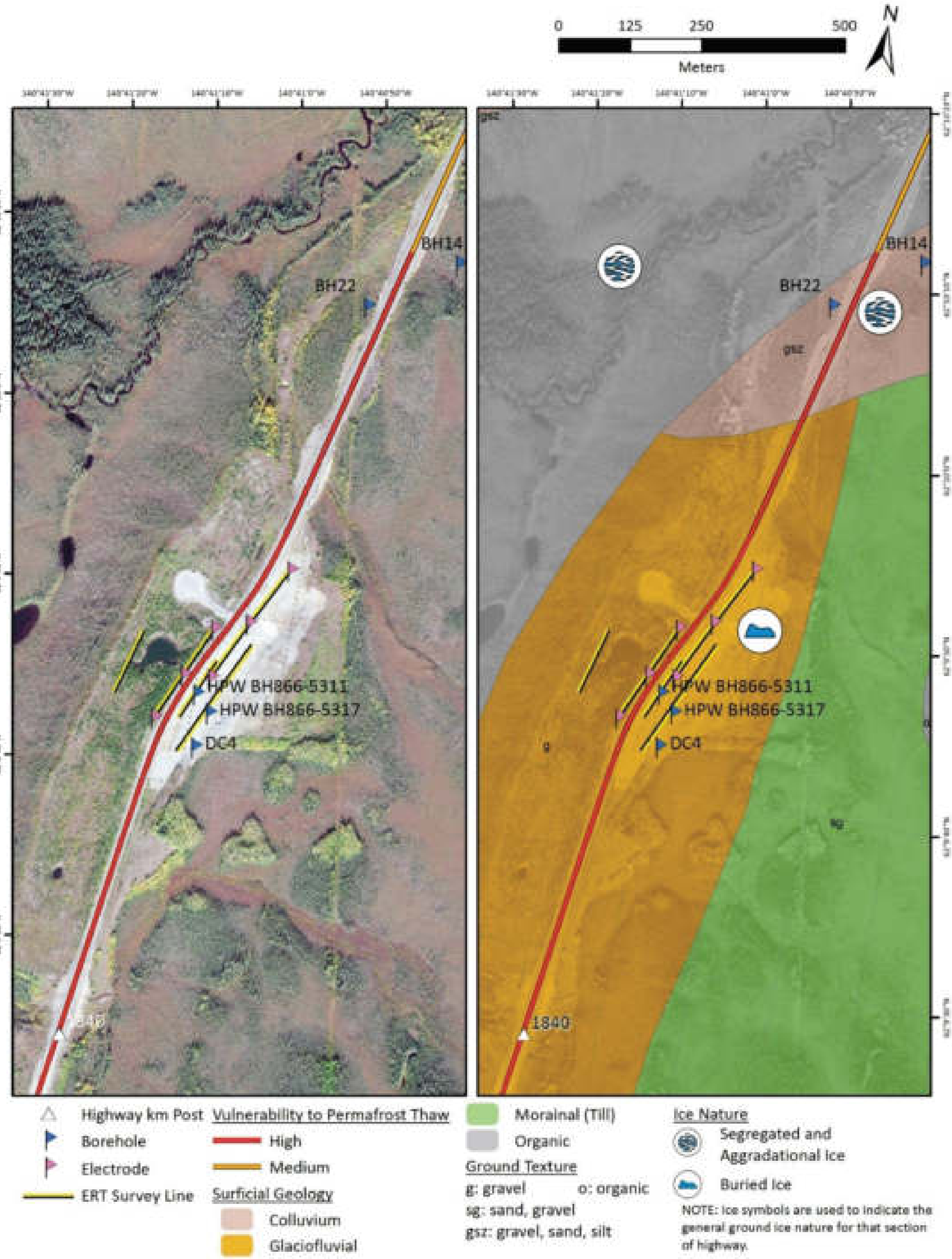


Figure 4.2.1. Vulnerability maps of Site 2 (satellite imagery and surficial geology)

4.2.1 Surficial geology and permafrost characterisation

- This highway section is underlain by moderately resilient permafrost (-0.9°C).
- The section crosses a glaciofluvial unit that is highly vulnerable to thaw settlement due to the presence of massive ice observed 10 m below the ground surface.

4.2.1.1 Geology

This section of the road is located on a glaciofluvial deposit. It is surrounded by various surficial materials, including glacial (moraines), organic sediments, and colluvium (Figure 4.2.1).

The glaciofluvial deposits of the Dry Creek area were deposited at the margin of a melting glacier. Glaciofluvial deposits are formed when glacial sediments are washed out of the terminus of a glacier by meltwater and deposited. The glaciofluvial outwash consists mainly of gravel and sand, and is typically assumed to have low vulnerability to thaw. However, this geomorphological context also provides conditions for the burial and/or formation of massive ice bodies, such as those observed on site.

A morainic complex is located on the east side of the site. It was laid by an ancient glacier and consists of heterogeneous sediment (sand and mixed fragments in a finer matrix). The complex is comprised of coarse sediment that does not favour the development of ground ice, thereby limiting vulnerability to thaw. Permafrost developed epigenetically after the glaciers retreated, from the top to the bottom, which has constrained its thickness. Because the glaciofluvial deposit was deposited after the moraine, it is possible that it overlays some moraine. Also, in some specific settings, such as in the margins of glacier, moraines can contain significant amounts of ground ice.

Organic soils are found on the west side of the site. They developed in poorly drained depressions and overlying glaciofluvial material. Organic soils are often the most ice-rich, as demonstrated by the occurrence of thermokarst lakes and ponds. However, the section under consideration does not cross them, so they likely do not pose a threat to the road or embankment.

Colluvium and other slope deposits are located at the North of the section, overlying the glacial deposits. Colluvial deposits also contain a mix of coarse and fine material, but permafrost has developed syngenetically, with each new sediment layer. This increases the risk of thaw sensitivity.

4.2.1.2 Permafrost

The glaciofluvial unit underlying the road section appears to be at the origin of the settlement observed at the site. When gravel was extracted from the slope facing the rest area at Dry Creek, it almost immediately triggered thermokarst processes. This is surprising, because such coarse material would normally contain very little ground ice. However, both borehole logs and ERT surveys showed the occurrence of ground ice.

The logs of the HPW boreholes drilled in Fall 2015 and photos of the cores collected are presented in Figures 4.2.2 to 4.2.5. Borehole HPW 866-5311 (Figure 4.2.2 and 4.2.3), located closest to the road, has a gravelly layer to 3 m depth, followed by massive ice from 3 m to 9.4 m depth, below a gravelly layer. Sediment underlying the ice grades into finer materials with increasing depth, becoming a silt from 17.4 to 19.8 m, the end of the borehole.

Borehole HPW 866-5317 (Figure 4.2.4 and 4.2.5), located closest to the bluff, shows the presence of massive ice from the depths of 4.6 to 9.4 m, below a gravelly layer. The sediment underlying the ice also grades to finer material with increasing depth, becoming a silt from 15.8 to 19.8 m, the end of the borehole. In both boreholes, the basal silty unit shows the presence of ice and water content ranging from 23.5 to 29.5 %, meaning that this unit is also thaw sensitive.

The ERT surveys show highly resistive material, which is an indicator of ice (Figure 4.2.6A to E):

A. Survey conducted west of a developing thermokarst pond that is west of the road.
   - Highly resistive material was observed from about 7–20+ m depth. Resistivity values are in the range of frozen till, but thermokarst processes are an indicator of a significant amount of ground ice.

B. Survey conducted between the Thermokarst Lake and the road.
   - Highly resistive material was observed, starting at about 5 m depth. The horizontal extent of the highly resistive material mostly matches the dimensions of the thermokarst pond, and suggests the presence of ice-rich, thaw sensitive soil.

C. Survey conducted just east of the road.
   - Highly resistive material was observed starting at about 3 m depth (contact with ICE and gravel in HPW 866-5311 log) with a sharp increase of resistivity in at about 6 m depth (contact with ICE and silt in HPW 866-5311 log). The changes in resistivity are corroborated by borehole the observations.

D. Survey conducted just east of the road; a southward continuation of survey C.
   - Highly resistive material was observed at both ends of the survey suggesting a gap in ice-rich material with a return to ice-rich soil at each end of the survey. The northern highly resistive area aligns with the the southern edge of the thermokarst pond that is located west of the road.

E. Survey conducted closer to the bluff to the east of the road.
   - A highly resistive body was observed at about 5 m depth (contact with ICE and sand in Borehole HPW 866-5317). Resistivity values are the highest observed, in the order of 10^6 Ohm.m, which is typical of a massive ice body.

Figure 4.2.7 shows a preliminary map of the distribution of the ground ice based on the ERT and Borehole observations.

Ground temperatures were obtained for the site from a borehole drilled by Pr. G. Doré's team that was later instrumented with a logger and thermistor wires. From November 2014 to April 2015, a 4-channel logging system was used. In May 2015, the system was upgraded with an additional 4-channel logger allowing ground temperature measurement at 8 depths. Mean monthly ground temperatures from of November 2014 to October 2015 are presented in Table 4.2.1; ground temperature curves and profiles are shown in Figures 4.2.8 and 4.2.9. Permafrost appears to be warm, with a temperature of -0.9°C at 11.8 m depth.

Table 4.2.1. Ground temperature recorded at DC04

	0.0 m	0.5m	1.0 m	2.0 m	3.0 m	5.0 m	8.0 m	11.8 m
2014								
November		-7.2°C			-0.8°C	-0.3°C		-0.8°C
December		-7.3°C			-1.3°C	-0.3°C		-0.7°C
2015								
January		-8.9°C			-2.4°C	-0.9°C		-0.8°C
February		-9.0°C			-3.3°C	-1.5°C		-0.6°C
March		-7.5°C			-3.4°C	-1.6°C		-0.7°C
April	4.6°C	-1.2°C	-0.4°C	-1.6°C	-2.4°C	-1.7°C	-1.0°C	-0.8°C
May	14.0°C	5.3°C	0.5°C	-1.0°C	-1.0°C	-1.4°C	-1.0°C	-0.9°C
June	16.2°C	10.8°C	6.1°C	-0.6°C	-0.5°C	-1.0°C	-1.0°C	-0.9°C
July	16.6°C	12.3°C	8.3°C	-0.4°C	-0.3°C	-0.7°C	-0.9°C	-0.9°C
August	11.9°C	9.9°C	7.2°C	-0.1°C	-0.2°C	-0.6°C	-0.8°C	-0.9°C
September	5.9°C	4.5°C	3.6°C	-0.1°C	-0.1°C	-0.5°C	-0.7°C	-0.9°C
October	-0.8°C	-0.3°C	0.8°C	-0.3°C	-0.1°C	-0.5°C	-0.7°C	-0.9°C

SUBSURFACE EXPLORATION AND TEST REPORT	**Alaska Highway - Site 2 - Dry Creek West area**	SOURCE/TP#: **866-5311**
Boart Longyear	Establishment of Baseline Data, km 1840 RHS	PROJECT NO: 552-202021-0601-05-1
Sonic Drill	Coordinates: Z Nm Em	ELEVATION: m
SAMPLE TYPE: UNDISTURBED, DCPT, AUGER, BULK, SPT, CORE		

SOIL DESCRIPTION	Depth (m)
POORLY GRADED GRAVEL with SAND -Brown, loose, damp -Trace fiberous organics	
	1
POORLY GRADED GRAVEL with SILT and SAND -Dark brown, moist, compact -Light brown, dry, loose	2
POORLY GRADED GRAVEL with SAND -Dark brown, moist, compact	
ICE and GRAVEL -~80% Grey-brown, highly fractured Ice ICE -Grey, cloudy, fractured -White	3
-Brittle	4
-Light brown, clear	
-Cloudy, highly fractured - individual crystals distinct	5
ICE and SILT -Vs, white cloudy ice, 30mm thick -Grey silt, 10mm thick SNOW and ICE -Layerd, snow 20mm thick, and ice 5mm thick -White, clear, slight fracture in solid ice	6
SILTY SNOW and ICE -Dirty grey snow, clear white ice Snow and ICE -Snow, white, cloudy, 2mm thick sections -Ice, white, clear, some bubbles, 2mm thick sections	7
-Harder	8
-Silt seam ICE and SILT -Vs, 2mm Ice, 10mm Silt (Nbe) -Ice is white, and clear -Grey silt	9
SILTY SAND with GRAVEL -Grey, subangular -Vx, white cloudy crystals	11
SILT with SAND -Dark grey, hard, Nbe	12
SILTY GRAVEL with SAND -Dark grey, hard, Nbe	13
SILTY SAND with GRAVEL -Dark grey, hard, Vx	14
-Nbe -Nbn	15
-Nbe	
-Nbn	16
-Nbe	17
SILT with SAND -Dark grey, Nbn SILT -Vr	18
SILT with SAND -Nbn	19
END of HOLE	

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	COMPILED BY: R.Stilwell	Complete: 9/13/2015
	REVIEWED BY:	Pit #: Page 2 of 2

Figure 4.2.2. Log of borehole HPW 866-5311 (west).

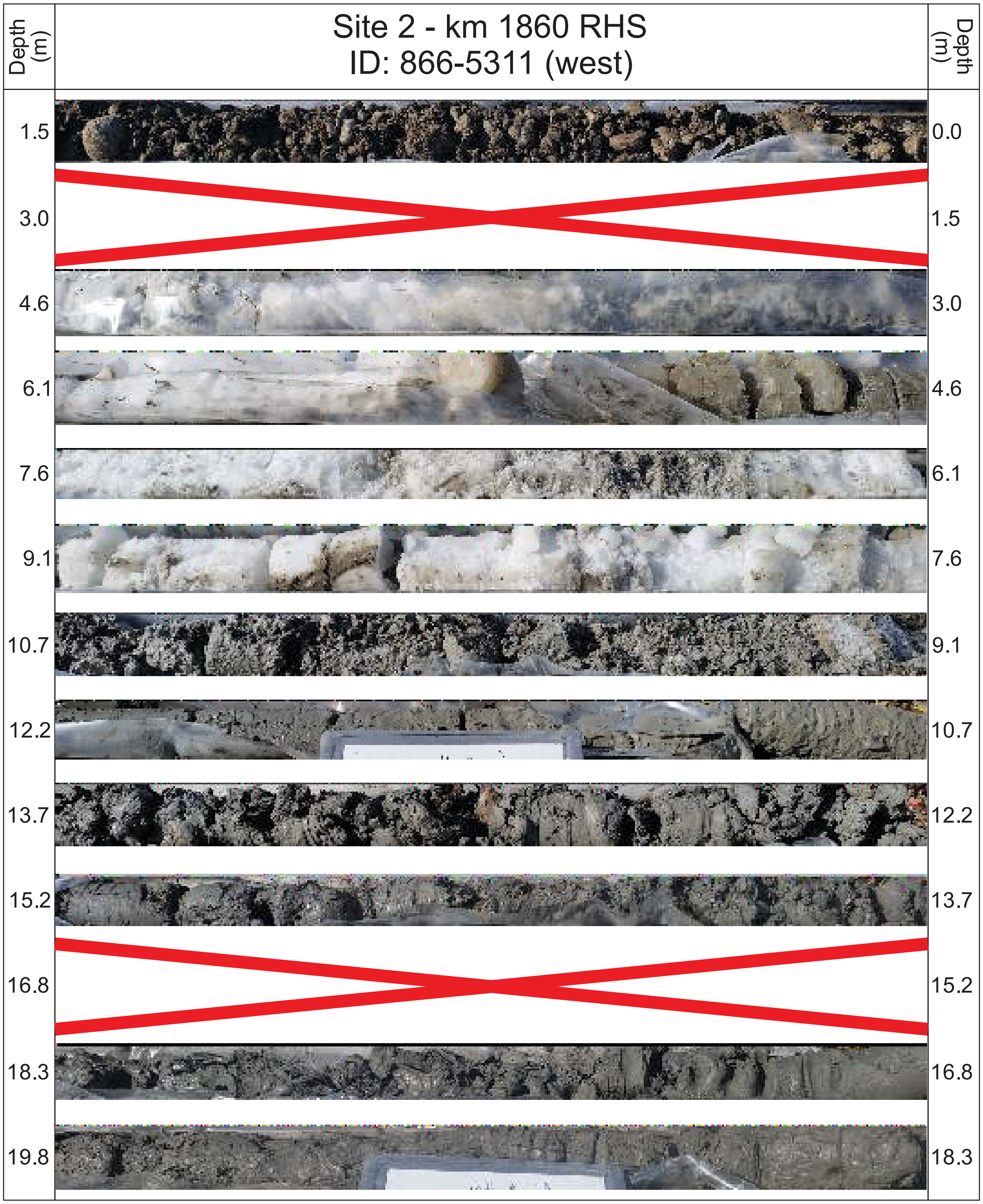


Figure 4.2.3. Core collected from borehole HPW 866-5311 (west).

SUBSURFACE EXPLORATION AND TEST REPORT	**Alaska Highway - Site 2 - Dry Creek East area**	SOURCE/TP#: **868-5317**
Boart Longyear	Establishment of Baseline Data, km 1840 RHS	PROJECT NO: 552-202021-0601-05-1
Sonic Drill	Coordinates: Z Nm Em	ELEVATION: m

SAMPLE TYPE: UNDISTURBED, DCPT, AUGER, BULK, SPT, CORE

SOIL DESCRIPTION	Depth (m)
WELL-GRADED GRAVEL with SILT and SAND -Dark brown, loose, moist	0
	1
SILTY GRAVEL with SAND -Dark brown, moist, compact	2
WELL-GRADED GRAVEL with SILT and SAND -Dark brown, wet to saturated, compact	3
	4
ICE with SAND -Brown-grey, cloudy, highly fractured ice	5
ICE -White, cloudy, fractured ICE, trace SAND -Grey brown, clear, fractured	6
ICE, trace SILT -Grey brown, fractured, clear ICE -White, clear, hard, some bubbles	7
ICE, trace sand -Grey-brown. clear, fractured ICE -White, cloudy-clear, semi fractured	8
ICE with SILTY SAND with GRAVEL -Brown gravel, Clear white Ice (Vr) ~50%	9
SILTY GRAVEL with ICE -Dark grey silty gravel -40% Vx, white, cloudy	

SOIL DESCRIPTION	Depth (m)
SILT -Silt seam, Nbe, 20mm	
SANDY SILT with GRAVEL -Dark grey, hard -Vx	11
	12
<<L>SILTY GRAVEL with SAND -Dark grey, compact, Nbe	13
	14
-Nbn	15
SILT -Dark grey, firm, Nbn -Vr, Clear, white	16
-Nbn	17
	18
-Nbe -Vx, Cloudy, white	19
-Vx-Vr, Clear, to cloudy, white	
END of HOLE	

Yukon — Highways and Public Works, Transportation Engineering Branch	LOGGED BY: R.Stilwell	Termination Depth: 19.8m
	COMPILED BY: R.Stilwell	Complete: 9/16/2015
	REVIEWED BY:	

Figure 4.2.4. Log of borehole HPW 866-5317 (east).

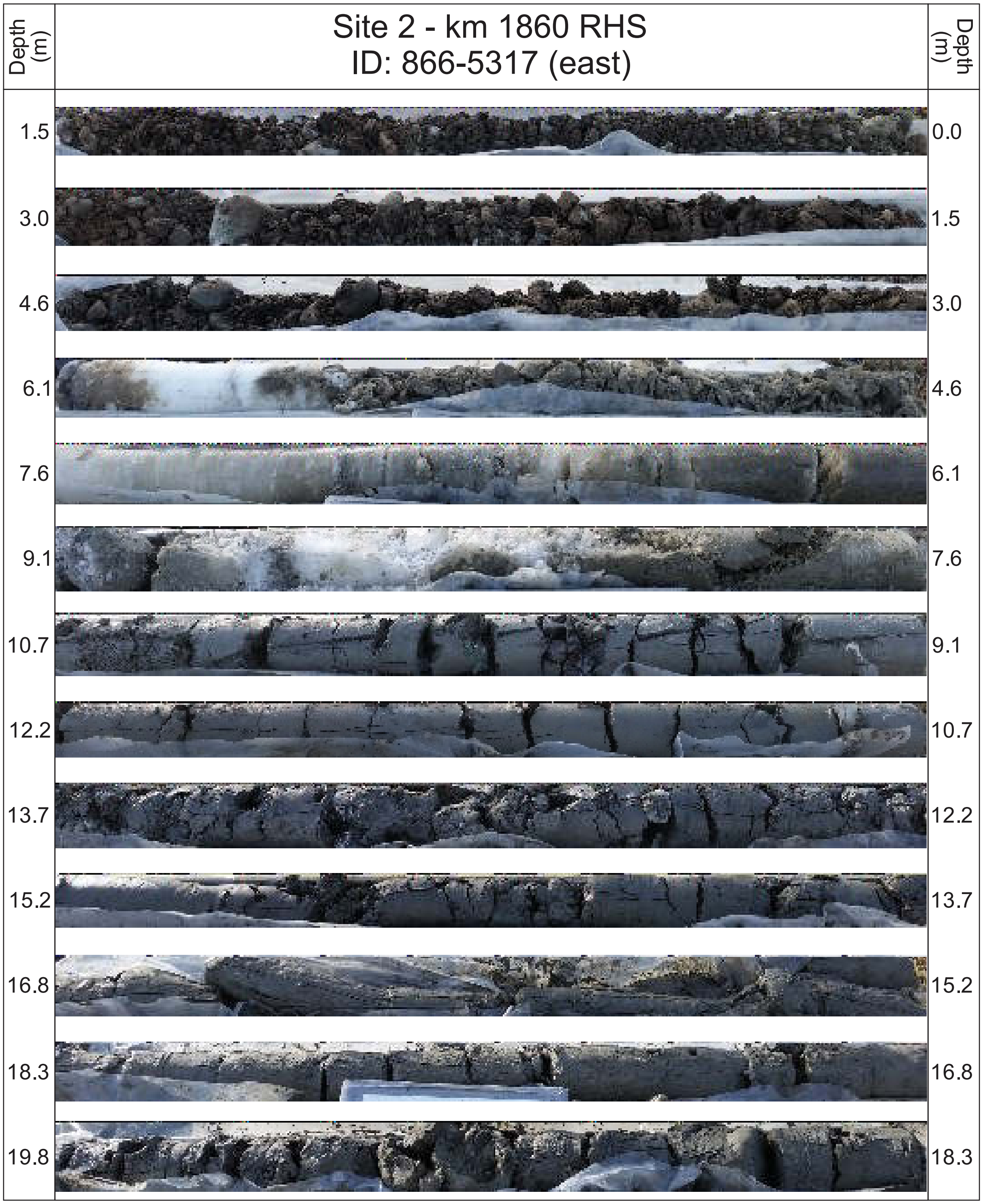


Figure 4.2.5. Cores collected from borehole HPW 866-5317 (east).

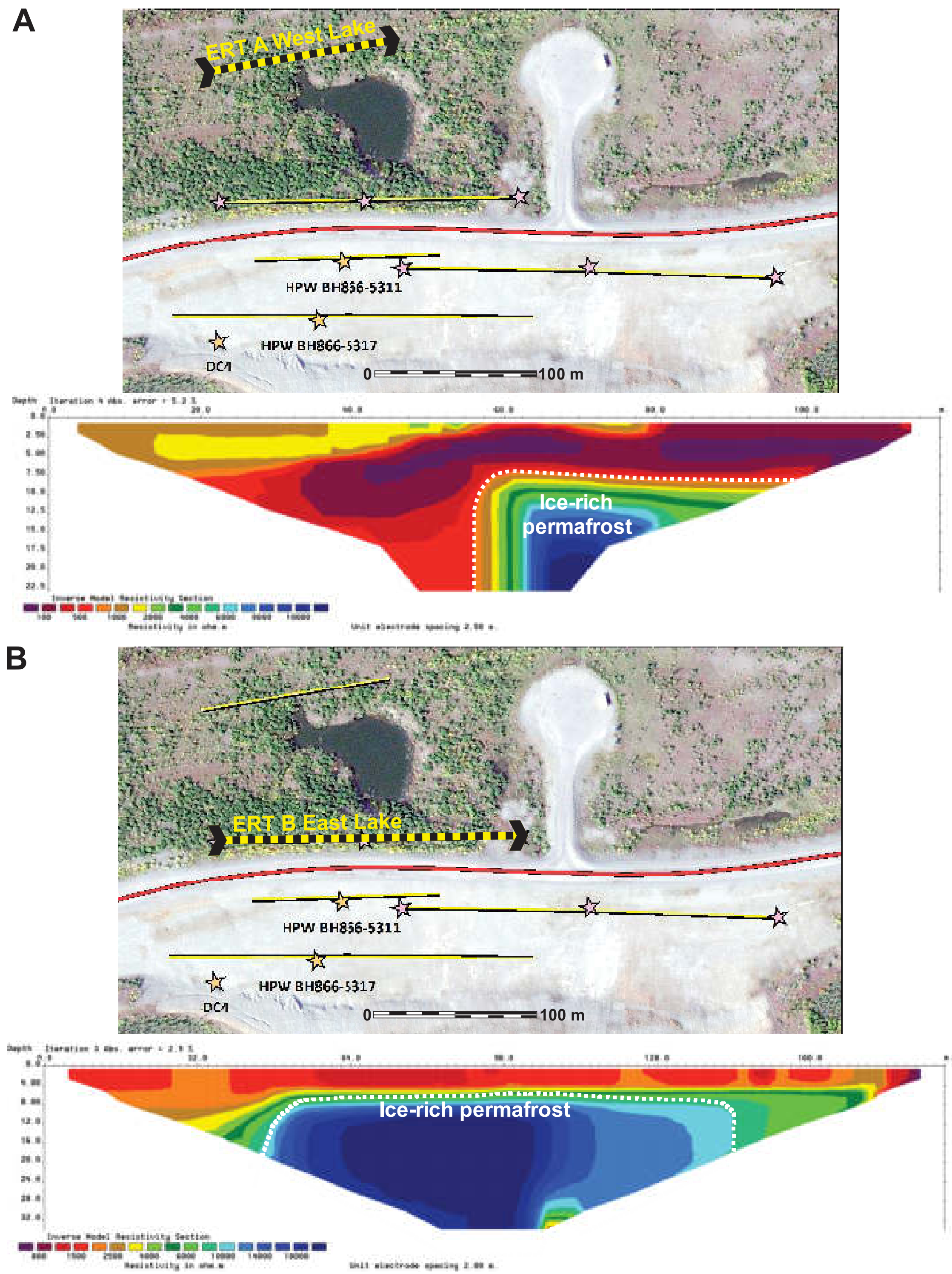


Figure 4.2.6. ERT Surveys performed at Dry Creek rest area site for A) West of the thermokarst lake; and B) East of the thermokarst lake.

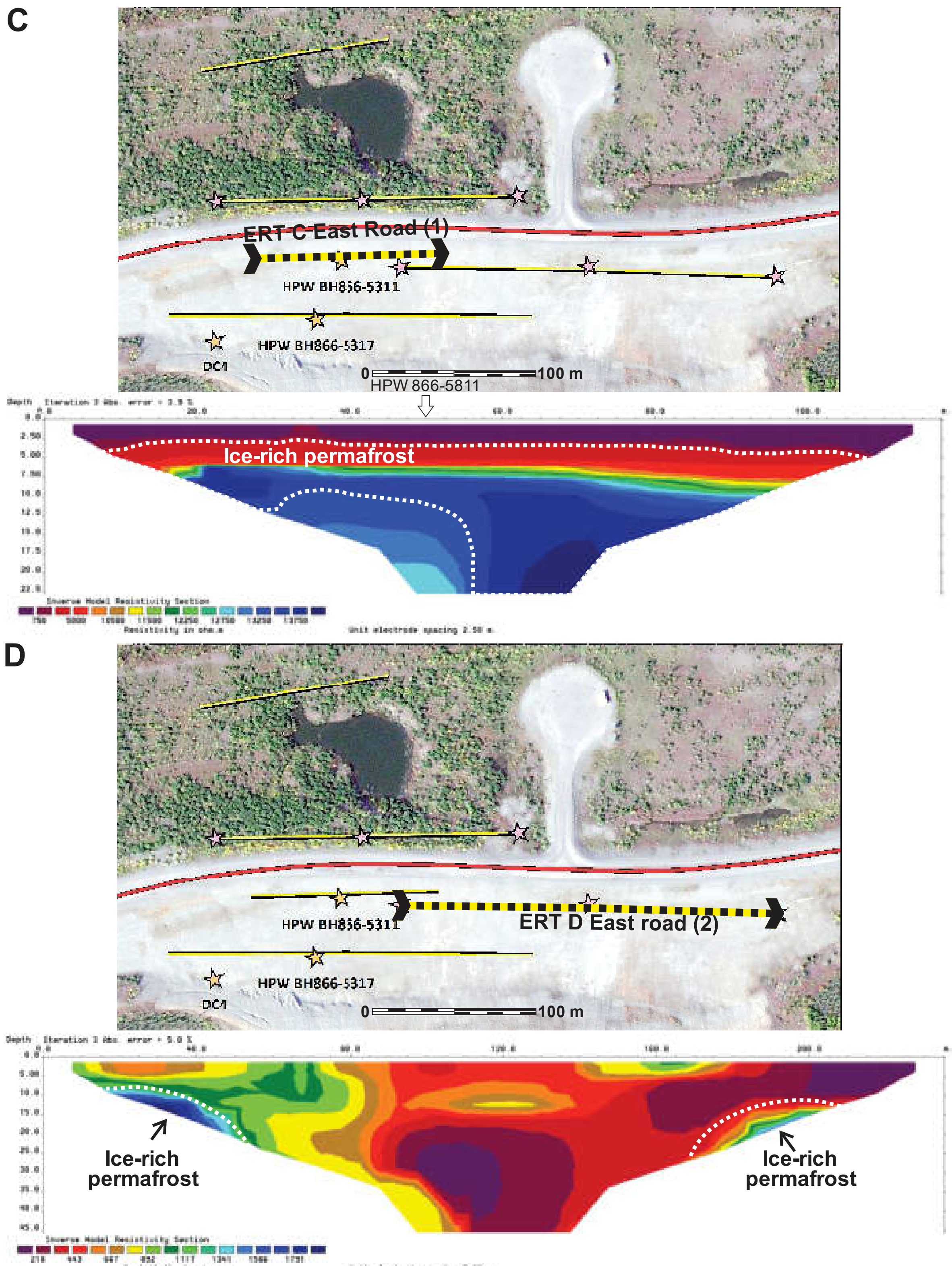


Figure 4.2.6 (cont.). ERT Surveys performed at Dry Creek rest area site for C) East of the road (North); and D) East of the Road (South).

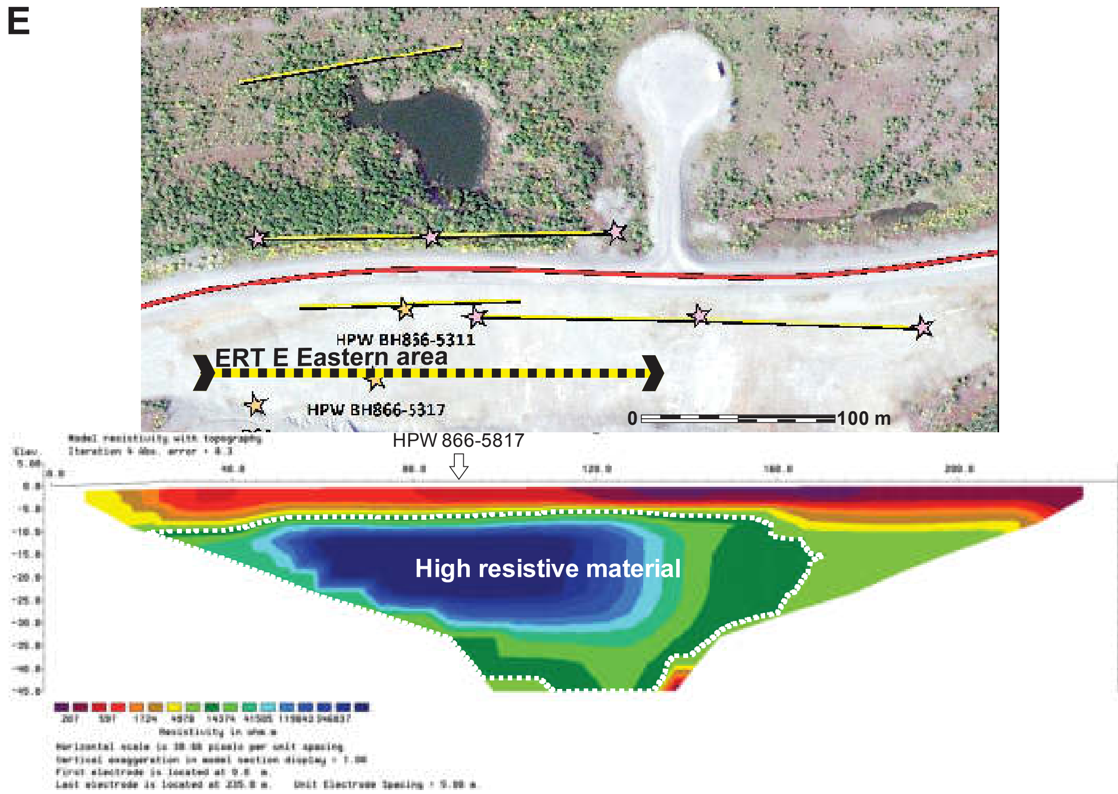


Figure 4.2.6 (cont.). ERT Surveys performed at Dry Creek rest area site.

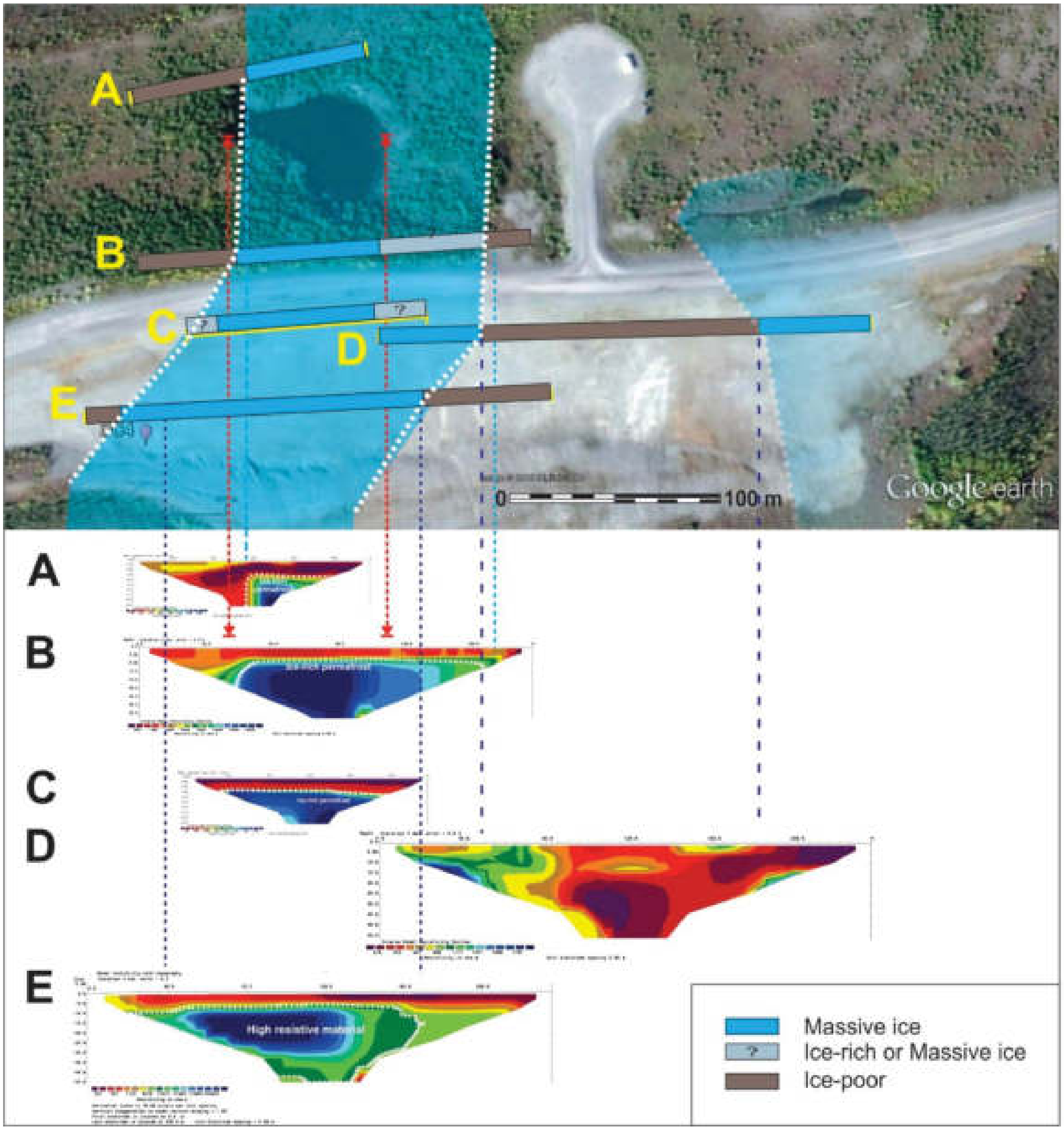


Figure 4.2.7. Preliminary map of the distribution of the ground ice based on the ERT and Borehole observations.

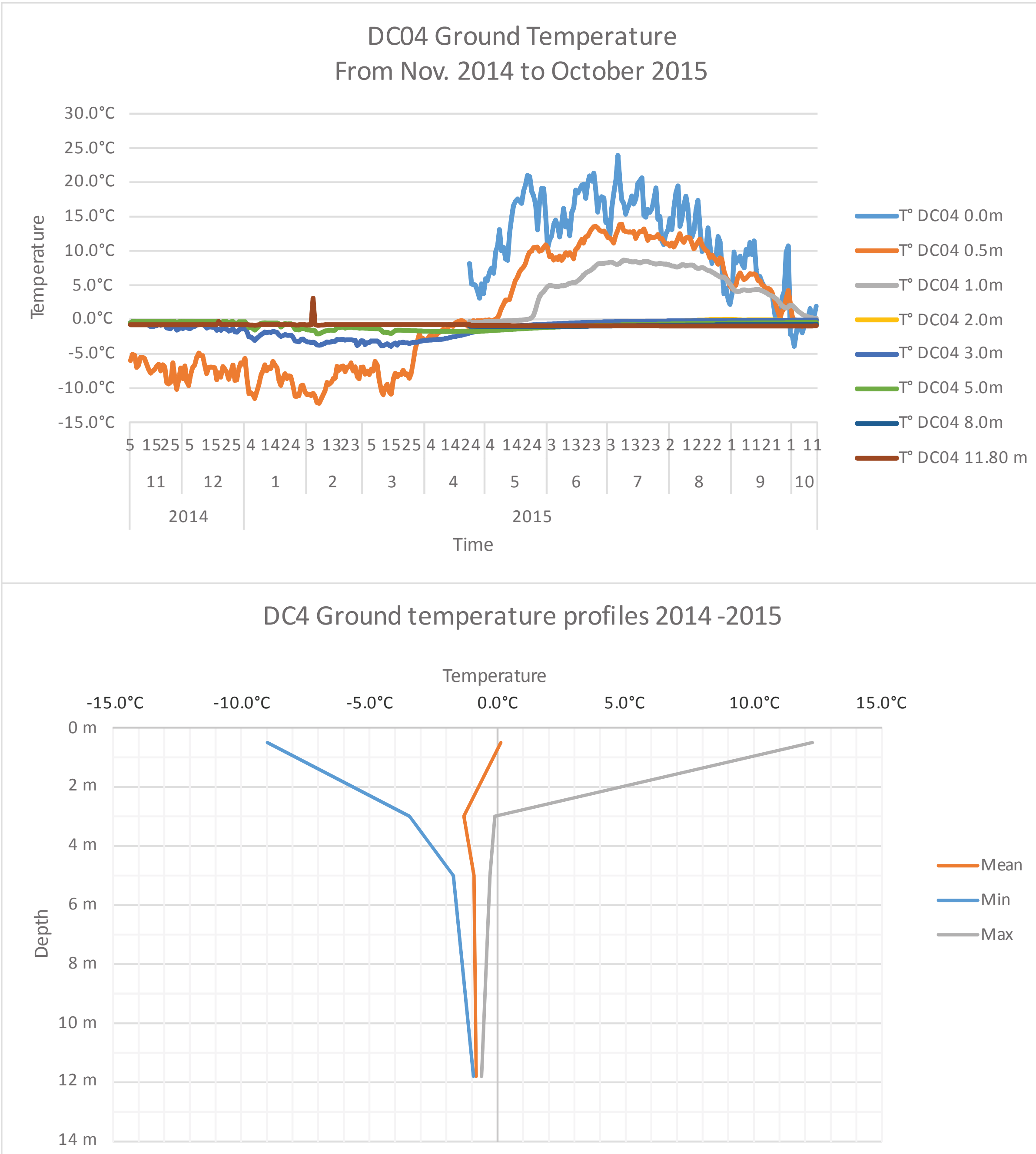


Figure 4.2.8. Ground temperature recorded in DC4 from November 2014 to October 2015.

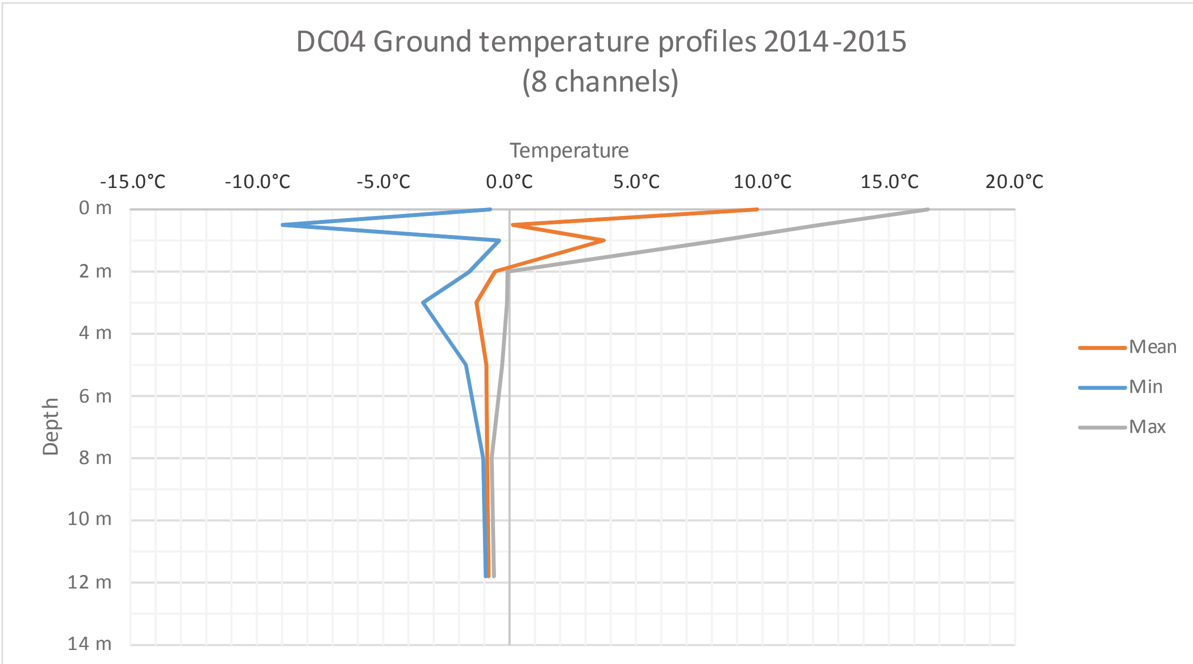


Figure 4.2.9. Ground temperature recorded in DC4 from November 2014 to October 2015 including 8-channels data.

4.2.2. Adaptation design

4.2.2.1. Site configuration

This embankment cross section in Figure 4.2.10 is located at km 1840.6. In this area, gravel has been excavated to provide materials for road construction. Following the excavation, several thermokarst depressions have occurred within the excavated area, and a pond has formed nearby the excavated area. This is an indication that there is likely massive ice and/or ice-rich permafrost.

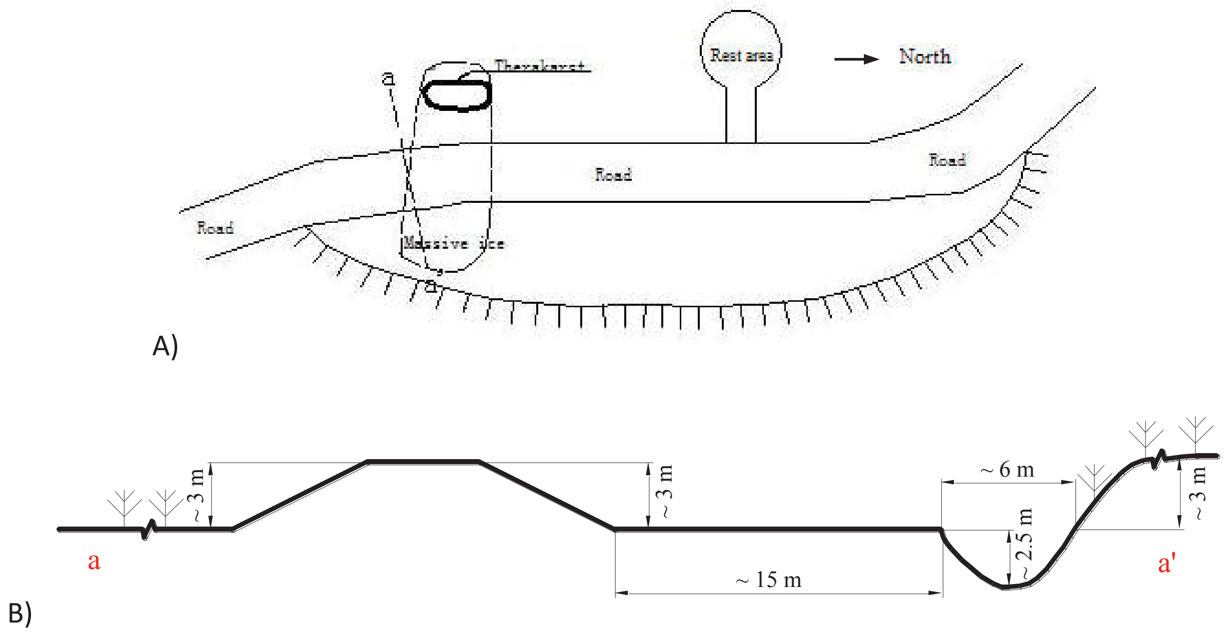


Figure 4.2.10. Schematic illustration of the Dry Creek adaptation site for A) Localisation of proposed embankment cross section in transverse profile; and B) a-a' embankment cross section, km 1840.6

Figure 4.2.11 A shows general views of the site. The vegetation, comprised mainly of shrubs and trees covers, is present on both sides of the embankment (Figure 4.2.11 B); yet it differs in density on each side. On the right hand side when facing north, there is a low density of shrubs and other plants from the toe of embankment to the edge of the gravel pit due to recent earthwork activities, therefore, the gravelly ground surface is often apparent. On the left hand side, looking north, there is a high density of trees covering about 90% of the land area (Figure 4.2.11 B).

A large thermokarst pond is present on the Left Hand Side of the road. Its formation is attributable to the melting of a substantial amount of ground ice thaw following the construction activities.


A)


B)

Figure 4.2.11. Dry Creek adaptation site, km 1841.3 for A) General view of the site, facing west; and B) Left and right hand sides of the embankment, facing north

4.2.2.2 Site thaw-sensitivity

Borehole observations, ERT and microgravimetric surveys led at the Dry Creek site have confirmed the existence of ice-rich ground and the presence of large massive ice bodies underlying the area and the road embankment. The massive ice is located as little as 3 m below the surface.

The permafrost underlying the site is ice-rich, but also relatively warm, with a ground temperature of -0.9°C recorded at borehole DC4. Based on GCMs, temperature and precipitation are expected to increase by 1.5-2.5°C and 20-50 mm, respectively, by the 2030s; 2.5-4.5°C and 40-80 mm, respectively, by the 2050s. Considering the important excess ice content, relatively warm ground temperature, the >20 m thickness of permafrost, this site is highly susceptible to thaw. The projected climate will further disrupt the ground thermal equilibrium resulting in serious failures, such as settlement and localized ground collapses.

Permafrost degradation is already observed at this site, and the thermokarst pond continues to enlarge at the left hand side of highway. Some failures, such as small uneven settlement and longitudinal cracking have occurred.

The detailed information about site 2 is summarized in Table.2.

Table 4.2.2. Detailed information of adaptation site 2

Permafrost distribution (ice-rich)	Mean Annual Ground Temperature (°C)	Height Difference (m)	
		Right Side	Left Side
6 m ~ more than 20 m	-0.9	3.0	3.0
Excess ice content (Maximum)	**Soil Types**	**Climate Warming(°C)**	
		2030s	**2050s**
54%	Gravelly to fine-grained	1.5 to 2.5	2.5 to 4.5
Vegetation (Land Cover)	**Surficial Material**	**Drainage Condition**	
Variable - About 80%	Glaciofluvial	No Ditch – generally dry	

4.2.2.3 Adaptation suitability

The thaw of ice-rich soils and massive ice bodies threatens the integrity of the embankment. The massive ice is widespread on the site with evidence of permafrost degradation observed along the embankment and at the entrance of the rest area. Climate warming will exacerbate the thermokarst processes. Longitudinal cracking and differential settlement is likely to occur.

The permafrost temperature at the Dry Creek site is relative warm (-0.9 °C), but remains close to the -1°C threshold desired for remediation. The ice-rich ground represents a significant reserve of latent heat to build on to stabilize or delay permafrost thaw. Permafrost has been proven to have a thickness exceeding 20 meters, as observed in the borehole. If permafrost thaw will result in significant damage on the site, the resulting settlement will also contribute to a feedback of adverse effects detrimental to permafrost such as water concentration increasing heat flow through permafrost, or increased snow accumulation preventing heat extraction. The section is straight, without important curves or slopes. There is no lateral flow, but a thermokarst pond is developing, which has to be controlled. Consequently the site is considered as a good candidate for adaptation.

4.2.2.4 Adaptation strategy

To preserve the stability of this road, aggressive adaptation techniques are required. Based on the considerations given in sections 3.1 and 3.2 (application conditions), ACE, Thermosyphons, HAS and HD, are the recommended techniques for the Dry Creek site. Based on considerations given in section 3.2 and on local conditions, the selection order of proposed mitigation techniques, are:

1. ACE (U shape – Figure 4.2.12)
2. Thermosyphons (Figure 4.2.13)
3. HD with HAS (Figure 4.2.14)

The adapted section extends from km 1840.55 to 1840.9 for a length of 300 m, including a 80 m section along the thermokarst pond, where thermosyphons are suggested for design No 2.

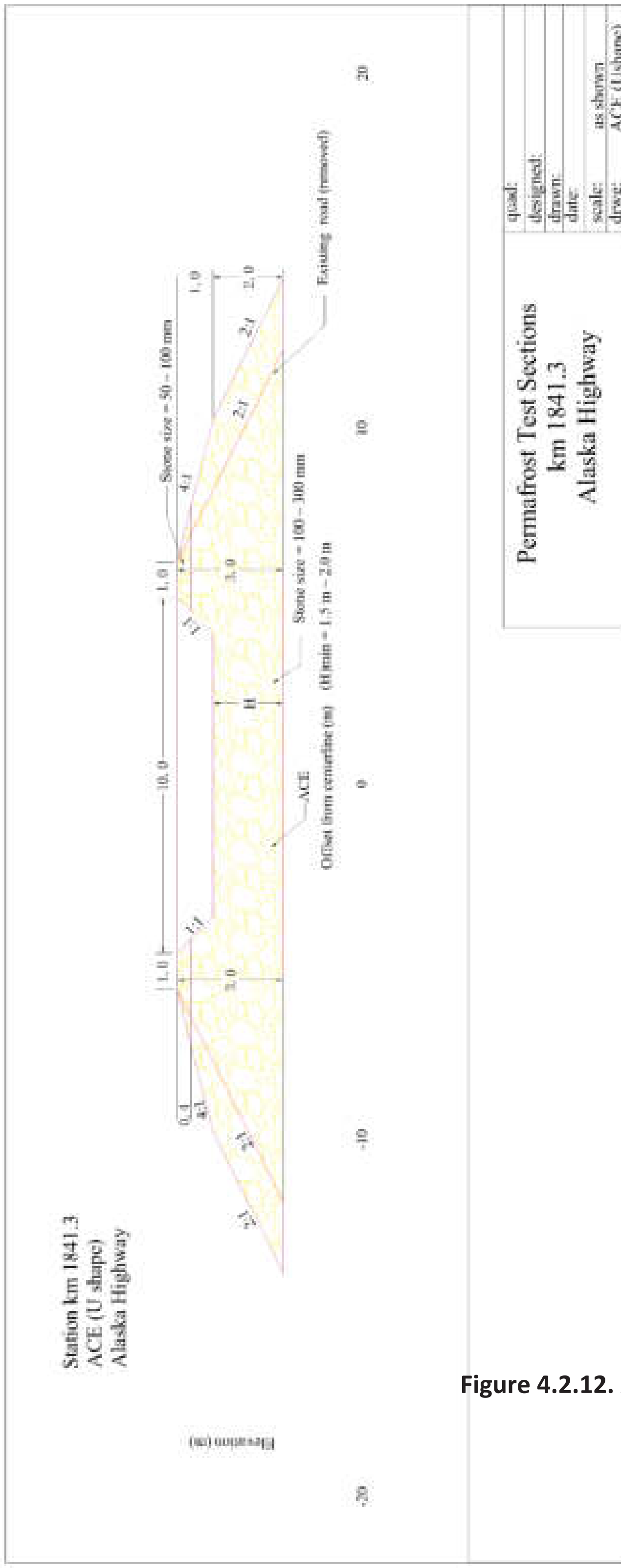


Figure 4.2.12. ACE (U shape)

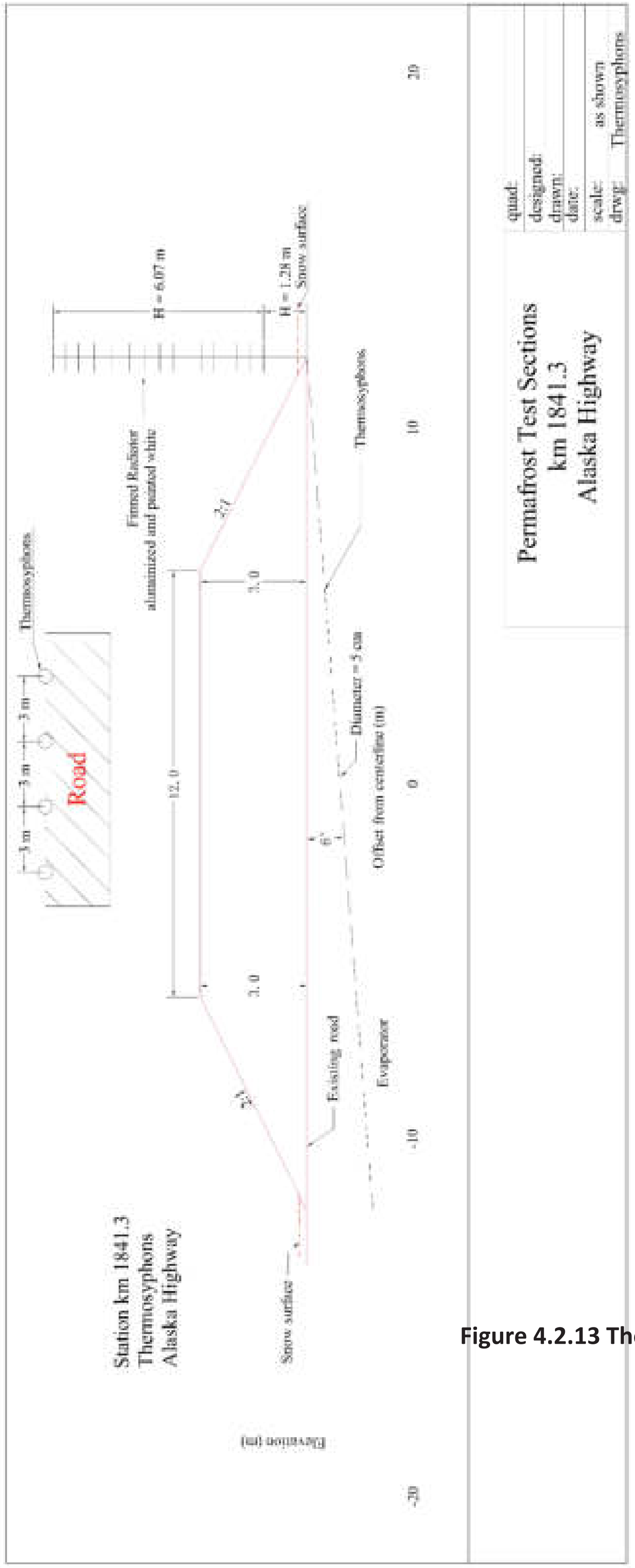


Figure 4.2.13 Thermosyphons

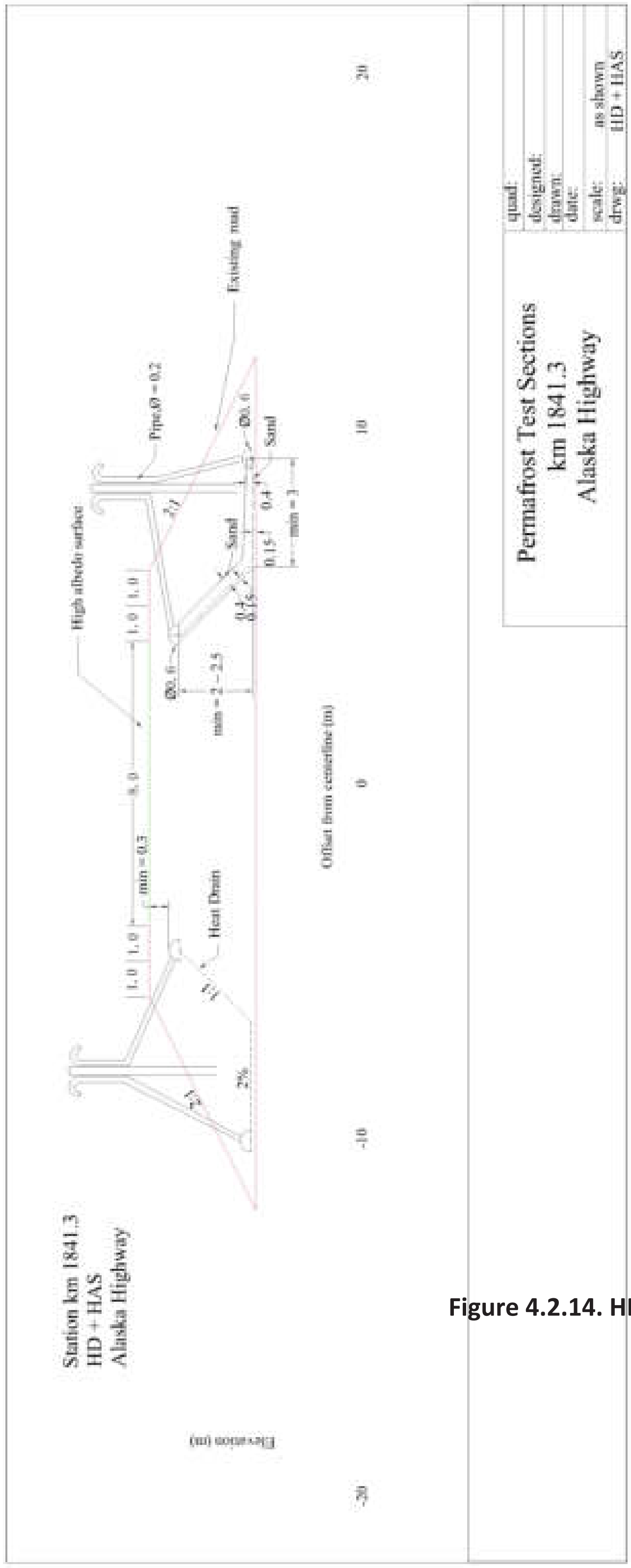


Figure 4.2.14. HD with HAS

4.3 SITE 3: ENGER CREEK, KM 1863

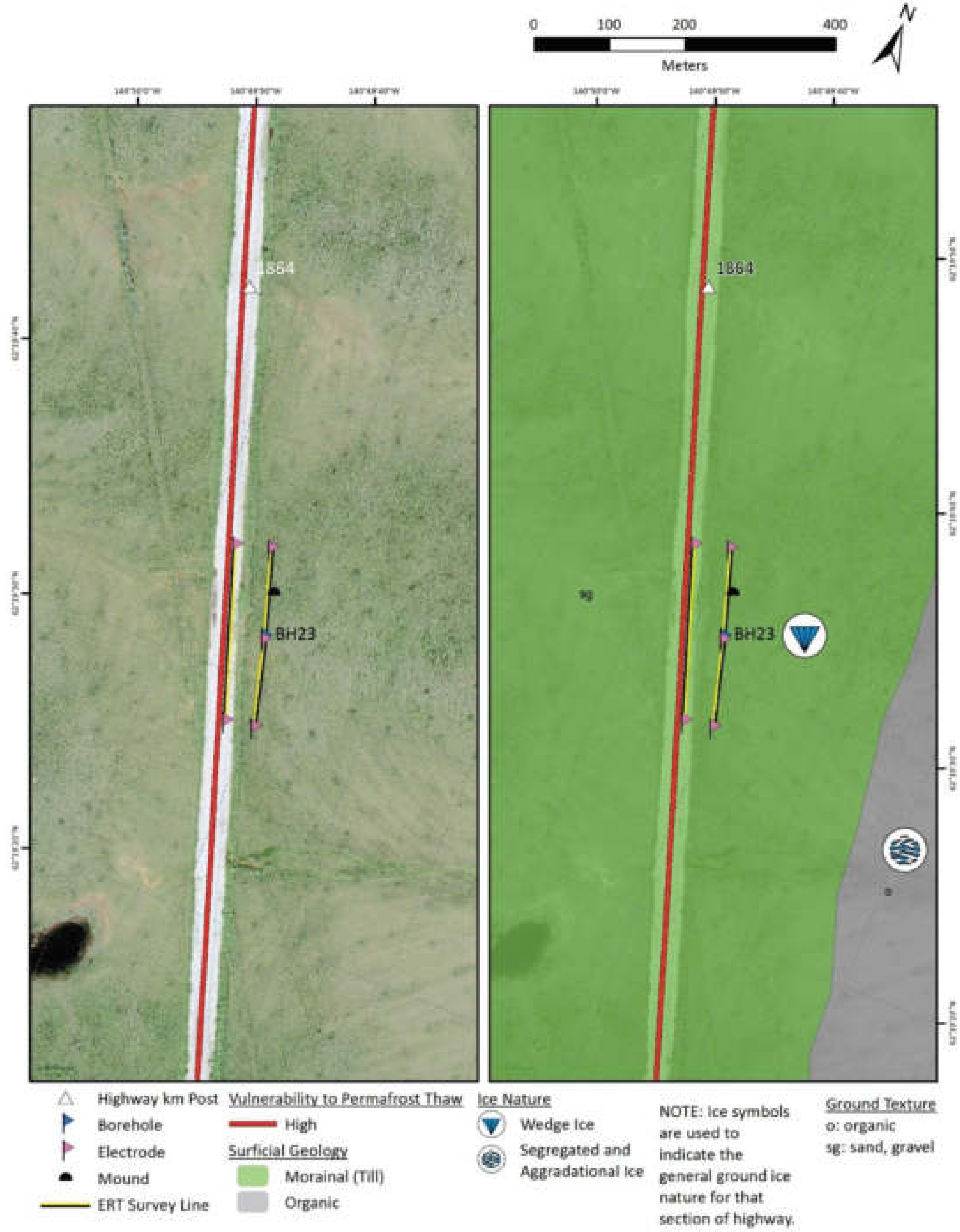


Figure 4.3.1. Vulnerability maps of Site 3 (satellite imagery and surficial geology)

4.3.1 Surficial geology and permafrost characterisation

- This highway section crosses relatively resilient permafrost (-1.6°C).
- This section is built on a geomorphic unit that is highly vulnerable to settlement if it thaws. The first 15 m of glacial and organic material are ice-rich.

4.3.1.1 Geology

This section of the road is located in a plain where various surficial geology materials deposited including moraines, and organic sediment (Figure 4.3.1).

The morainic complex was laid by ancient glaciers, during a glaciation prior to the McConnell glaciation (18,000 years ago). This unit consists of heterogeneous sediment (sand and mixed fragments in a finer matrix). Permafrost has had more time to develop within the ancient moraine than in the more recent glacial deposit. Because this section was not glaciated during the McConnell glaciation, surficial deposits were subject to colder climate than today. This led to the development of ice wedge complexes, and permafrost that is deeper than more recently glaciated areas. Also depressions have been filled by finer material from various origins.

Organic soils have developed in poorly drained depressions. Those soils are present at each side of the section, 300 m at the right and 900 m at the left when facing north. Their thermal properties favoured permafrost aggradation, while wetlands provide water supply that supported the growth of segregated ice.

4.3.1.2 Permafrost

This section of the highway is built over thaw-sensitive permafrost. Figure 4.3.2 presents the logs of borehole BH23. This borehole was drilled in the field. Figure 4.3.3 and 4.3.4 show the log and the pictures of the core, respectively, collected for borehole HPW 866-5310. This borehole was drilled at the toe of the embankment. The log of BH23 reports sandy silt and silty sand from the top to the base of the borehole (3.54 m). Excess ice content can be as high as 62%. Segregated ice is observed, but no wedge ice. However, wedge ice has been observed in the area on the wall of excavated ditches and from air photos. The log of HPW 866-5310 also reports sandy/silty sediment down to 5.7 m, then silty soil deposit down to 12.9 m, sediments then become progressively coarser from sandy silt to silty gravel down to 17.6 m, the bottom of the core. Vertical foliation is reported intermittently in ground ice at various depths between about 9 m to 12 m. Ground ice observations suggest an ice wedge complex located between 6.1 m and 16 m in silt.

Two ERT surveys where performed at this site: one in the field and one along the embankment. Both surveys are shown in Figure 4.3.5. The survey performed in the field show areas of ice-rich permafrost from the top down to a depth of about 15-17 m which is consistent with the borehole observations. The survey also suggests that either the base of permafrost, or the contact with bedrock is at about 35 m. The survey made along the embankment is inconsistent, showing highly resistive material below 15 m. The instrumentation may have been affected by the rainy condition on the day of the survey.

Ground temperature was recorded for the site in borehole BH23. Following the initial drilling, this borehole was deepened down to 9.45 m using a water jet drill. The borehole was instrumented with two 4-channel loggers in May 2015, allowing ground temperature measurement at 8 depths. The mean monthly ground temperatures from June 2015 to October 2015 are presented in Table 4.3.1, while ground temperature curves and profiles are shown in Figure 4.3.6. Permafrost appears to have potentially high thermal resilience with temperatures of -1.7°C and -1.6°C at depths of 8 and 9.45 m respectively. Based on the temperature profile from October 2015 the base of the permafrost can be extrapolated to a depth of about 33 m using a thermal gradient of +0.1°C per 1.45 m, between 8 and 9.45 m. While tentative, this extrapolation is consistent with the basal contact observed on the ERT survey performed in the field.

Table 4.3.1. Ground temperature recorded at BH23

	0 m	0.5m	1.5 m	3 m	4 m	6 m	8 m	9.45 m
2015								
June	15.5°C	2.4°C	0.0°C	-0.6°C	-0.7°C	-1.1°C	-1.2°C	-1.4°C
July	15.1°C	5.2°C	-0.6°C	-1.3°C	-1.5°C	-1.8°C	-1.8°C	-1.6°C
August	10.8°C	5.5°C	-0.5°C	-1.1°C	-1.4°C	-1.7°C	-1.8°C	-1.6°C
September	4.9°C	2.4°C	-0.4°C	-1.0°C	-1.3°C	-1.7°C	-1.8°C	-1.6°C
October	-1.2°C	0.0°C	-0.4°C	-0.9°C	-1.2°C	-1.6°C	-1.7°C	-1.6°C

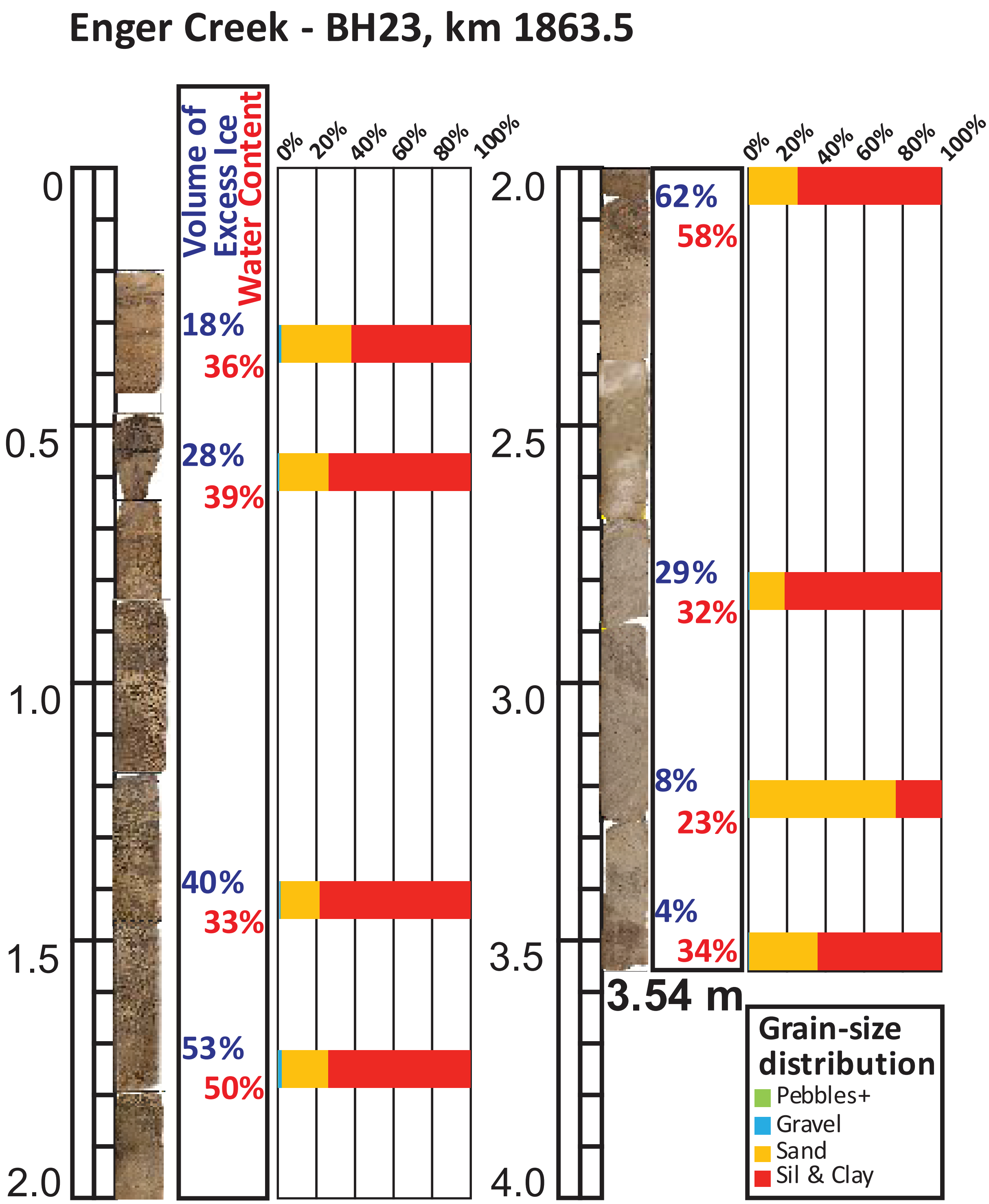


Figure 4.3.2. Log of borehole BH23.

SUBSURFACE EXPLORATION AND TEST REPORT	**Alaska Highway - Site 3 - Enger Creek BH23 area**	SOURCE/TP#: **866-5310**
Boart Longyear	Establishment of Baseline Data, km 1860 RHS	PROJECT NO: 552-2020 21-0601-05-1
Sonic Drill	Coordinates: Z Nm Em	ELEVATION: m

SAMPLE TYPE: UNDISTURBED, DCPT, AUGER, BULK, SPT, CORE

Depth (m)	SOIL DESCRIPTION
0	ORGANICS -Fiberous inclusions
	PEAT
	ORGANIC SILT -Brown, saturated, firm -Woody/fiberous inclusions -Frozen, Nbe
1.5	SILTY GRAVEL with SAND -Brown, subrounded, Vx -Nf -Vx ~20% -Nbn -Nf
4	SILTY SAND with GRAVEL -Highly weathered, Nbn
6.1	SILT -10% Vr - Clear, white, fractured -Brown silt
7	ICE and SILT -30% ice, clear, white, hard
7.6	SILT and ICE -10% Vr-Vx, individual crystals and sheets moving up in silt in curved planes -Vs, Vertical planes in column -Silt bedding planes are vertical, ~2mm wide -Vs, Vertical planes in column -Silt bedding planes are vertical, ~2mm wide -Nbn
12.3	SILT and ICE -Vs, ~5% Vertically bedded -Clear, white, fractured
14.1	SANDY SILT with GRAVEL -Brown, rounded, Nbn
16	SILTY SAND with GRAVEL -Nf
17.3	SILTY GRAVEL with SAND -Nbn -Nf -Nbn -Nf
19.8	END of HOLE

Yukon Highways and Public Works, Transportation Engineering Branch	LOGGED BY: R.Stilwell	Termination Depth: 19.8m
	COMPILED BY: R.Stilwell	Complete: 9/12/2015
	REVIEWED BY:	

Figure 4.3.3. Log of borehole HPW 866-5310

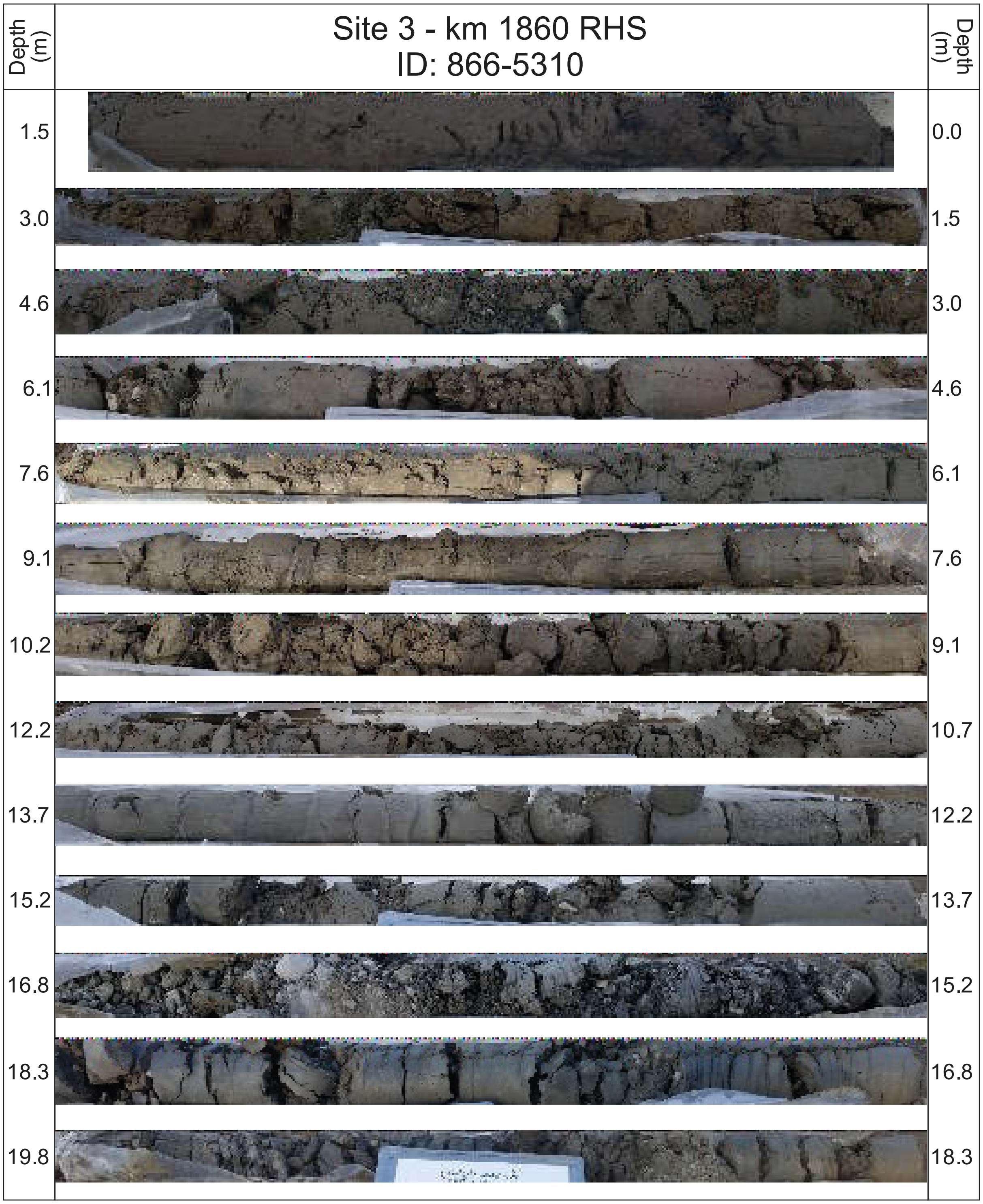


Figure 4.3.4. Cores collected from borehole HPW 866-5310

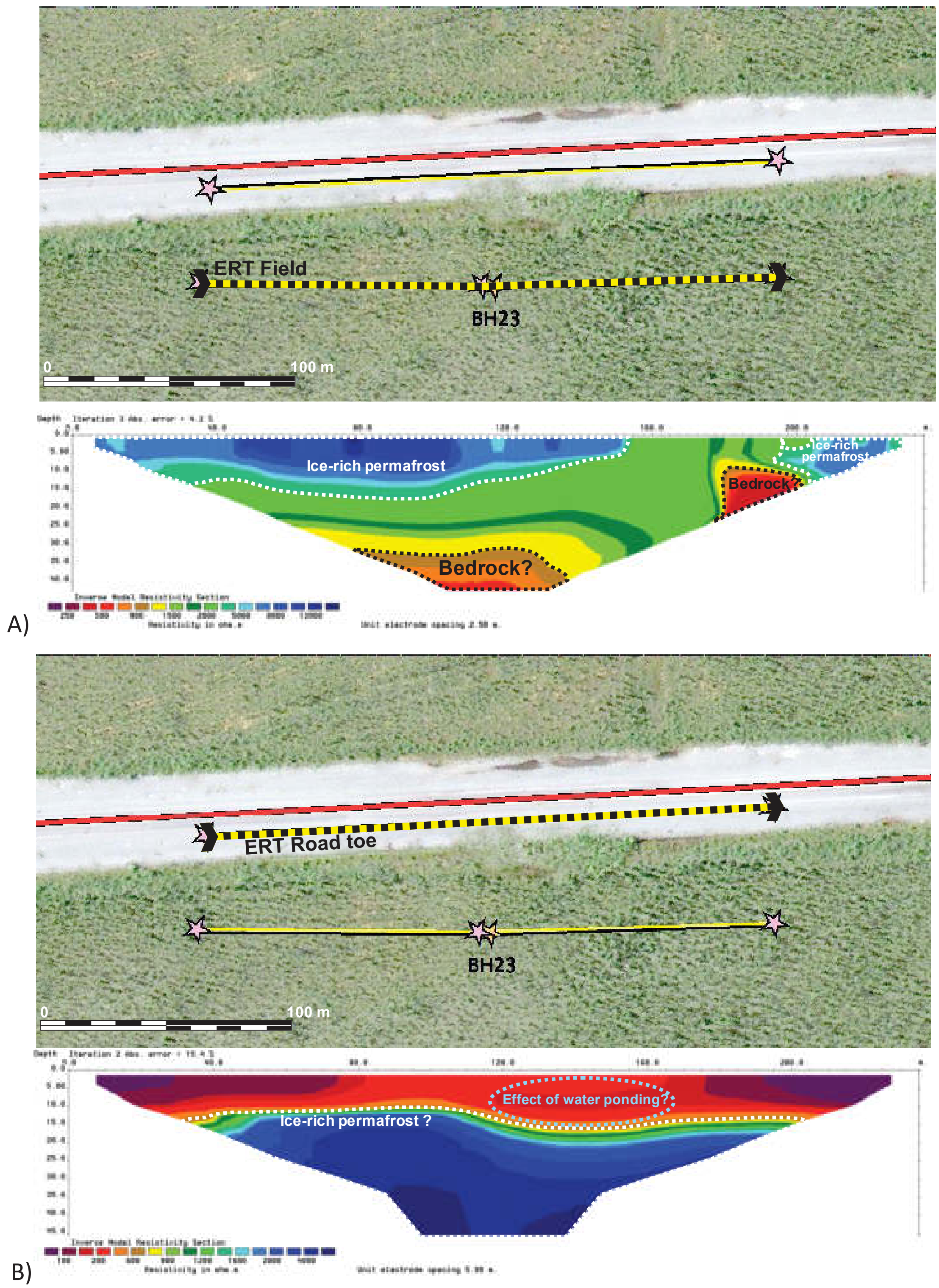


Figure 4.3.5. ERT Surveys performed at Enger Creek site for A) the field; and B) the toe of the highway embankment.

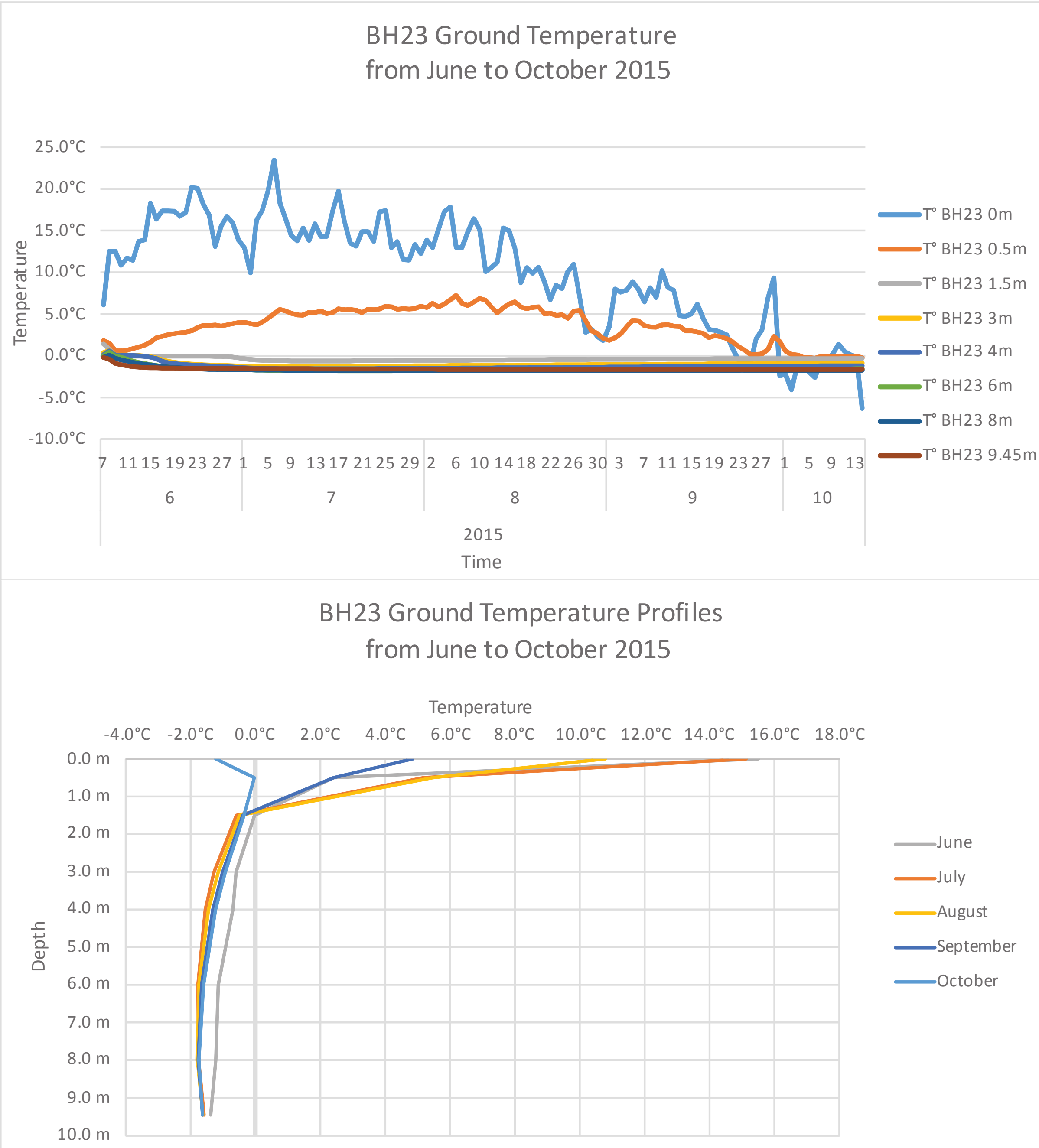


Figure 4.3.6. Ground temperature recorded in BH23 from June 2015 to October 2015.

4.3.2 Adaptation design

4.3.2.1. Site configuration

The site is located km 1863.5 on relatively flat terrain. As shown in the diagrams of Figure 4.3.7, the road is straight with the natural ground surface level being 1.0 m and 1.5 m below road surface on the left and right hand sides when facing north, respectively. Two ditches are present, one at a distance of about 9 m on the west (left hand side when facing north), and another at about 10 m on the right hand side when facing north. The ditches have been recently excavated and are in good working condition. The upper width and the depth of both ditches are about 2 m and 0.6 m, respectively. At this site, the terrain is smooth and there is no water ponding, hills or streams.

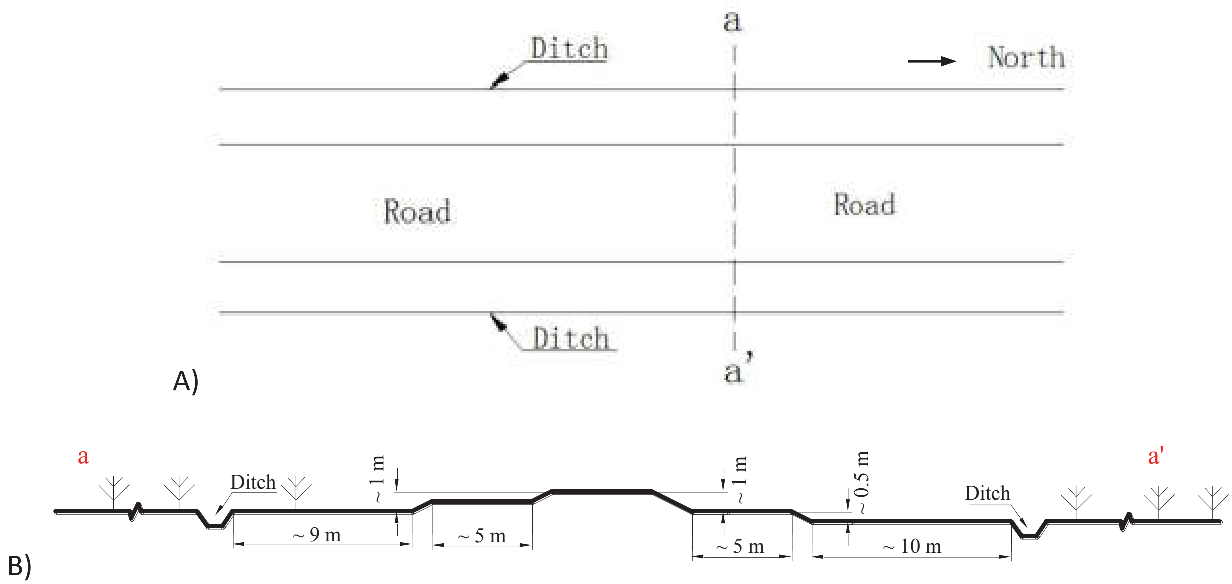


Figure 4.3.7. Schematic illustration of the Enger Creek adaptation site for A) Localisation of proposed embankment cross section and transverse profile; and B) a-a' embankment cross section at km 1863.5.

This road passes through a forested area and only the areas along the road are vegetation-free (Figure 4.3.8). Specifically, between the toe of the embankment and the ditches on both sides, the only vegetation is scarce grass, while the tree coverage outside the ditches is relatively thick.

A)

B)

Figure 4.3.8. Enger Creek adaptation site for A) Left and right sides of the embankment facing south; and B) Right and left sides of the embankment facing north.

4.3.2.2 Site thaw sensitivity

The boreholes drilled in the area display ice-rich fine-grained soils mostly consisting of thaw sensitive silts. Frozen conditions have been observed down to about 20 m, the end of the borehole. ERT surveys indicate ice-rich permafrost down to at least 15 m.

The ground temperature is about -1.6 °C, which is relatively warm. Based on GCMs, the temperature and precipitation will increase by 1.5-2.5 °C, and 20-50 mm, respectively, by the 2030s; 2.5-4.0 °C, and 40-80 mm, respectively, by the 2050s. Because this site is located on ice-rich, warm, thick permafrost, it can be defined as very susceptible to permafrost thaw. Permafrost degradation will affect the performance of the road.

The detailed information about Site 3 is summarized in Table 4.3.2.

Table 4.3.2. Detailed information of adaptation site 3

Permafrost distribution (ice-rich)	**MAGT (°C)**	**Height Difference (m)**	
		Right Side	**Left Side**
6 m ~ more than 18 m	-1.6	1.0	1.5
Excess ice content (Maximum)	**Soil Types**	**Climate Warming(°C)**	
		2030s	**2050s**
62% and possible wedge ice	Heterogeneous mix of sand and silt	1.5 to 2.0	2.0 to 2.5
Vegetation (Land Cover)	**Surficial Material**	**Drainage Condition**	
About 95%	Morainal	Two ditches	

4.3.2.3 Adaptation suitability

The permafrost is relatively warm (-1.6 °C), yet significantly below the -1°C threshold. The permafrost is thick (>20 m) and ice-rich (excess ice content >40%). There is very little surficial water around the site, and no evidence of extensive thermokarst processes at this time. This section of the road is built on flat and uniform terrain, without notable slopes or curves. The permafrost is thaw sensitive, and its thaw will result in damage to the highway. Therefore, adaptation measures are required to compensate for the effects of climate warming, and to make the embankment stable over a reasonable design period. This site meets or exceeds the criteria in Section 3, making Enger Creek site a good candidate for remediation.

4.3.2.4 Adaptation strategy

To protect the road, the mitigation method should be designed to compensate for climate warming (by reducing thaw rate), and to decrease soil temperature and promote permafrost aggradation.

Based on considerations given in section 3.2 (height requirement), the embankment is currently too thin for successful implementation of a convective technique, such as ACE, HD (1.0 m on right side; 1.5 m on left side). To meet the height requirement, the embankment could be slightly increased. Based on considerations given in section 3.2 and on local conditions, the proposed mitigation techniques are:

1. HAS with sun/snow shed (Figure 4.3.9)
2. HAS with insulation in shoulders (Figure 4.3.10)
3. HAS alone (risk of shoulder degradation – Figure 4.3.11)

The adapted section extends from km 1863.3 to 1864.3 for a length of 1000 m.

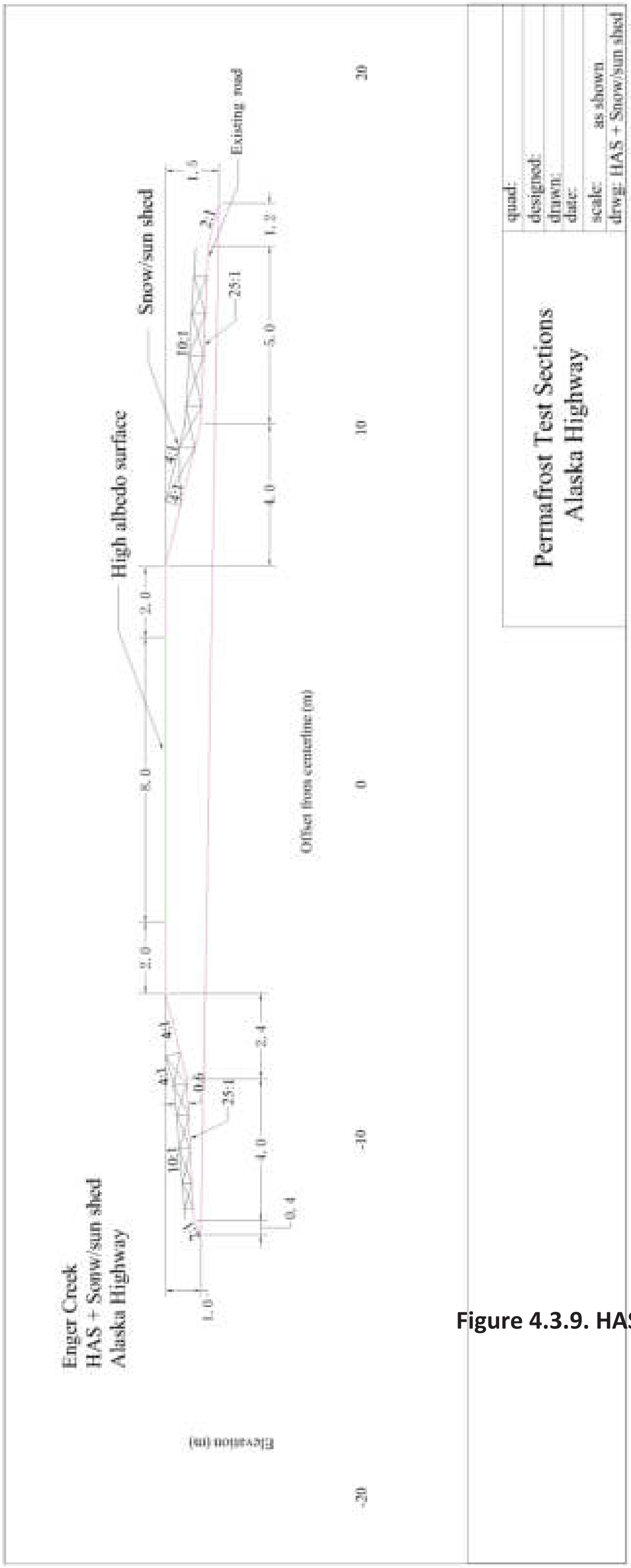


Figure 4.3.9. HAS with snow/sun shed

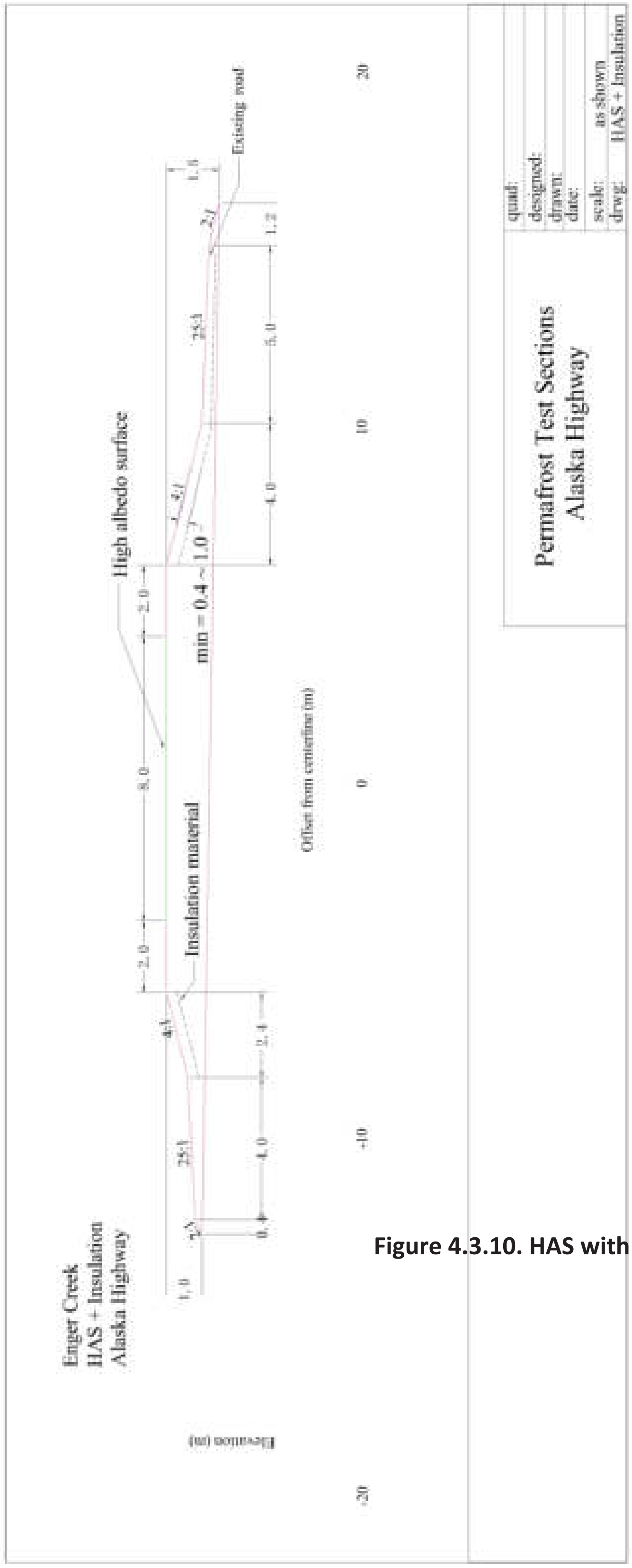
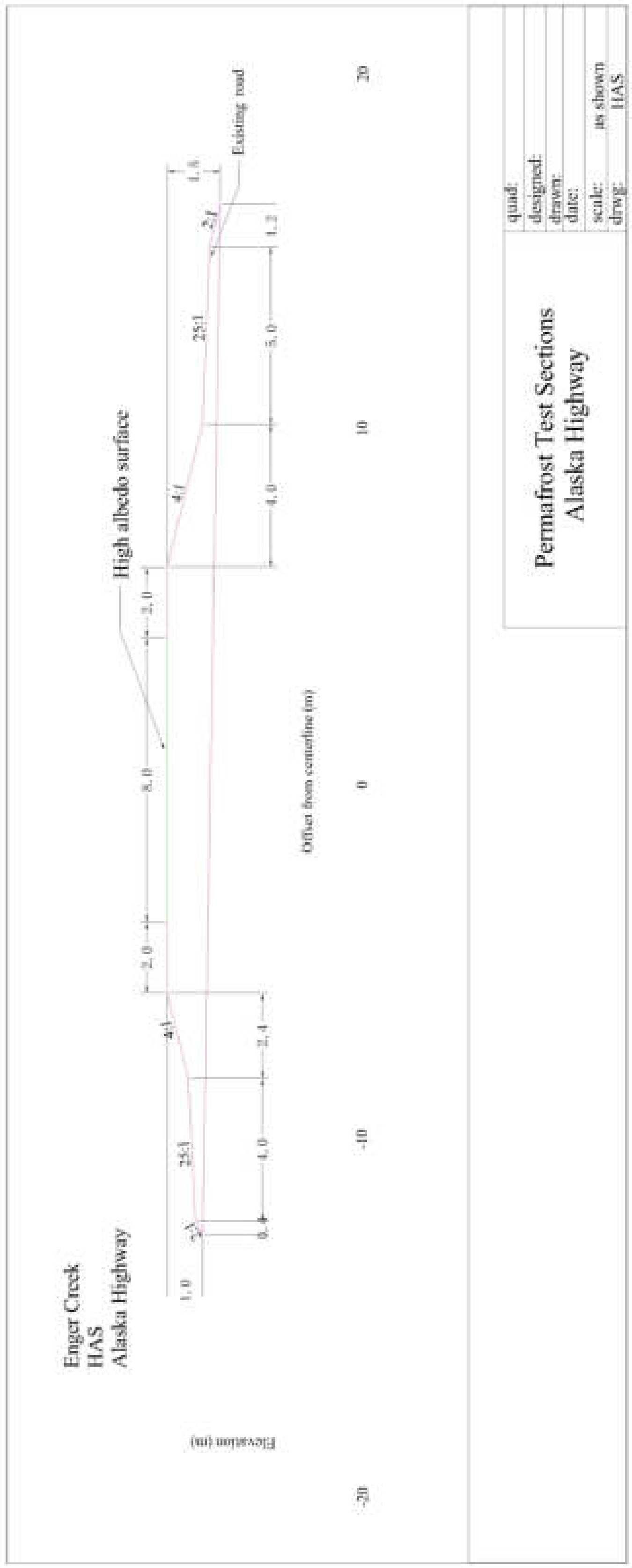


Figure 4.3.10. HAS with insulation in shoulders


Enger Creek
HAS
Alaska Highway
High albedo surface
Existing road
Offset from centerline (m)
Elevation (m)
Permafrost Test Sections
Alaska Highway
quad:
designed:
drawn:
date:
scale: as shown
drwg: HAS

4.4 ADAPTATION SITE 4: U.S. BORDER, BH13, KM 1896

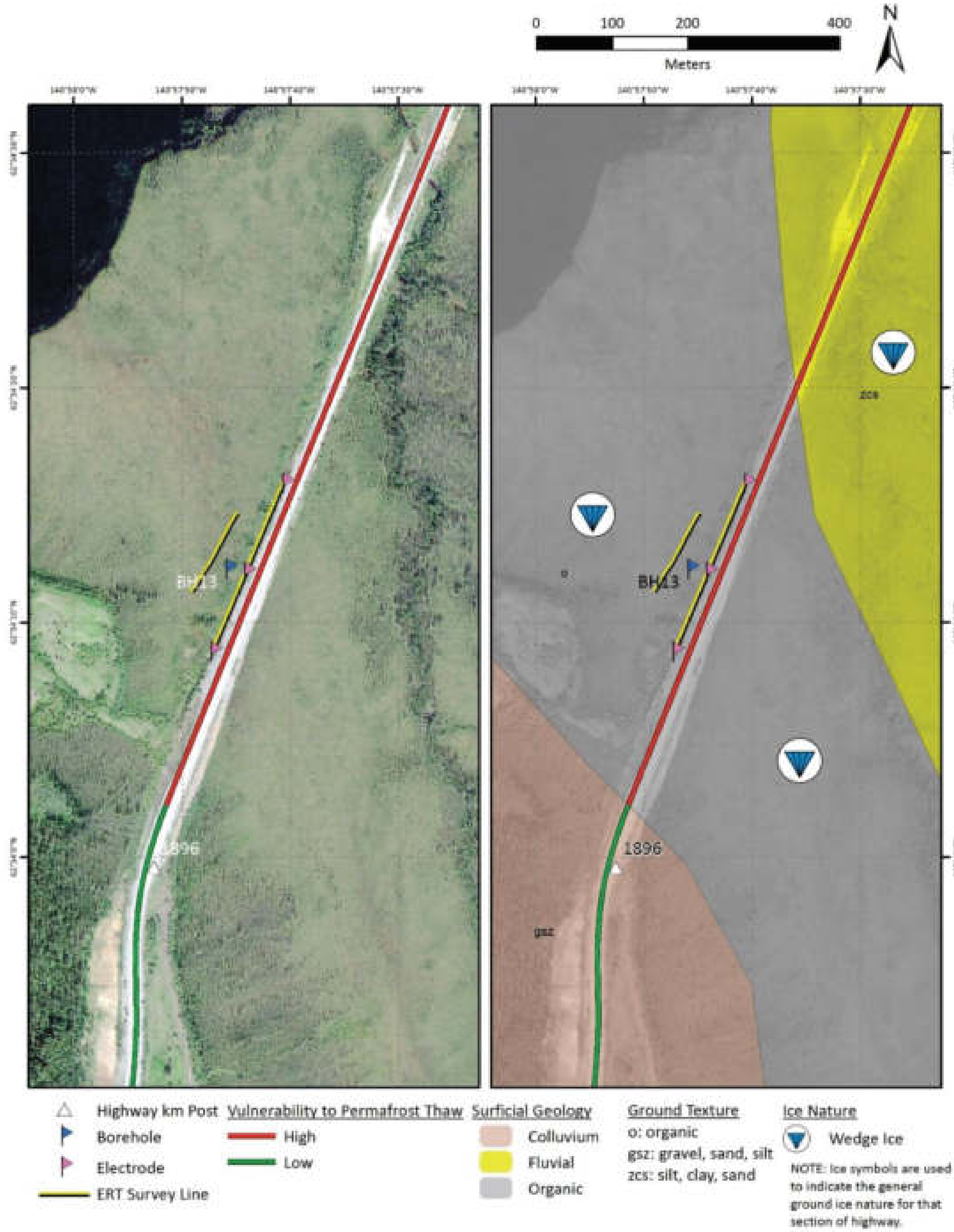


Figure 4.4.1. Vulnerability maps of Site 4 (satellite imagery and surficial geology)

4.4.1 Surficial geology and permafrost characterisation

- This highway section is underlain by relatively cold permafrost (approximately -2°C).
- This section crosses fluvial and organic units that are highly vulnerable to thaw settlement. Ice-rich permafrost can be expected as deep as 20 m. The permafrost base could be as deep as 60 m.
- Part of the section that crosses colluvium has low to medium vulnerability to thaw due to lower ground ice content and the thickness of the deposits.

4.4.1.1 Geology

This section of the road is located on terrain that was not glaciated during the McConnell glaciation. It alternates among various surficial geology materials, including colluvial, fluvial, and organic sediments (Figure 4.4.1).

Colluvium is present on the hill and at its foot at the south of the section. This unit is comprised of silt, sand and mixed fragments. A fluvial complex fills the valley bottoms at the north of the section and consists of sand, silt and clay. Some organic soils overlie fluvial material in the middle of the section.

The colluvial unit can be thaw-sensitive, but because it is located on a slope, thickness can be assumed to be relatively limited. However, the colluvium may overlie more sensitive material at some locations, meaning that slope movements and solifluction might cause problems for the road.

The fluvial and organic units are the most problematic. Fluvial deposits are fine grained and thick. Air photos and field observation show that they contain ice wedge networks. In addition, organic soils often overlie fluvial deposits, having developed in poorly drained depressions, which probably is the case in this section of the highway. The thermal properties of the organic soils favoured permafrost aggradation, and wetlands provide water that supports the growth of segregated ice. Organic units also display ice-wedge networks. Both fluvial and organic units show the development of thermokarst processes such as the lake located at about 350 m west of the section.

4.4.1.2 Permafrost

This section of the highway is built on thaw-sensitive permafrost. Figures 4.4.2 and 4.4.3 present the logs of boreholes BH13 and BH13B, respectively. These boreholes were drilled in the field.

Figures 4.4.4 and 4.4.5 show the log and the pictures of the core, respectively, collected for borehole HPW 866-5307. This borehole was drilled at the toe of the highway embankment. Borehole BH13 shows a gravelly-to-silty sandy peat in the first meter of the profile, then alternating layers of sandy sit and silty sand down to 4.2 m. From 4.2 to 4.4 m, the borehole passes through an ice wedge before returning to sandy/silty soil. The sediment appears to be organic rich; excess ice content is very high all along the profile, ranging between 57% and 99%. The log of BH13B is very similar to BH13, but it did not go through an ice-wedge. This may be because it is shallower. The log of HPW 866-53078 reports similar stratigraphy with silty ice-rich sediment alternating with organic and organic-rich level. This is similar to Site No 5 (BH12). Several ice-rich levels are present between 2.9 to 4.6 m , 5 to 6 m, and 15 to 18 m. Whereas the maximum amount of ground ice is about 25%, water content is relatively high between about 40 and 50% along the profile.

Two ERT surveys are shown in Figure 4.5.6; one in the field, 25 m west to BH13, and the other along the embankment. The survey performed in the field shows an area of high resistivity beginning at about 6 m depth and extending down to about 16 m. Based on both borehole and field observations, it can be interpreted that these highly resistive values represent ice-rich levels - likely ice-wedge formations. Resistivity values remain high below 16 m for the southern part of the profile indicating that ice-rich ground may also be present deeper in the profile. The survey made along the embankment is inconclusive, showing no clear resistivity pattern.

Ground temperatures were recorded from borehole BH13 using a 4-channel Hobo logger allowing ground temperature measurement at 4 different depths, beginning in October 2013. The mean monthly ground temperature for the recording period is presented in Table 4.4.1, while ground temperature curves and profiles are shown in Figure 4.4.7. Permafrost appears to be relatively cold at -2°C at the depth of 13.2 m. Mean annual ground temperature curves for 2014 were used to extrapolate permafrost base. A regression line was passed through the temperature curve from the depths of 3 to 13.2 m. Figure 4.4.8 shows the results of the extrapolation. Based on the regression, the base of permafrost is tentatively estimated to be at the depth of 58.5 m.

Table 4.4.1. Ground temperature recorded at BH13

	0.0 m	0.5 m	3.0 m	7.5 m	13.2 m
2013					
October		0.0°C	-1.5°C	-2.3°C	-2.0°C
November		-0.1°C	-1.4°C	-2.2°C	-2.0°C
December		-1.3°C	-1.3°C	-2.1°C	-2.0°C
2014					
January		-4.8°C	-1.6°C	-2.0°C	-2.0°C
February		-7.7°C	-2.6°C	-2.0°C	-2.0°C
March		-8.9°C	-4.0°C	-2.0°C	-2.0°C
April		-4.5°C	-4.5°C	-2.1°C	-1.9°C
May		-1.0°C	-3.6°C	-2.4°C	-1.9°C
June		-0.4°C	-2.8°C	-2.5°C	-1.9°C
July	13.2°C	0.7°C	-2.2°C	-2.5°C	-1.9°C
August	13.2°C	1.7°C	-1.9°C	-2.4°C	-2.0°C
September	6.0°C	1.1°C	-1.6°C	-2.3°C	-2.0°C
October	-3.5°C	0.0°C	-1.4°C	-2.2°C	-2.0°C
November	-13.8°C	-0.6°C	-1.3°C	-2.1°C	-2.0°C
December	-11.0°C	-1.7°C	-1.2°C	-2.0°C	-2.0°C
2015					
January	-14.5°C	-6.9°C	-1.7°C	-2.0°C	-2.0°C
February	-15.2°C	-10.6°C	-3.3°C	-2.0°C	-2.0°C
March	-8.6°C	-8.2°C	-4.5°C	-2.0°C	-2.0°C
April	3.8°C	-2.8°C	-4.6°C	-2.3°C	-1.9°C
May	13.1°C	-0.9°C	-3.7°C	-2.5°C	-1.9°C
June	15.1°C	-0.1°C	-2.9°C	-2.6°C	-1.9°C
July	15.9°C	1.5°C	-2.3°C	-2.6°C	-2.0°C
August	11.6°C	2.6°C	-1.9°C	-2.5°C	-2.0°C
September	5.3°C	1.3°C	-1.7°C	-2.4°C	-2.0°C
October	-1.2°C	0.2°C	-1.5°C	-2.4°C	-2.0°C

Valley Bottom Site – BH13, km 1896.3

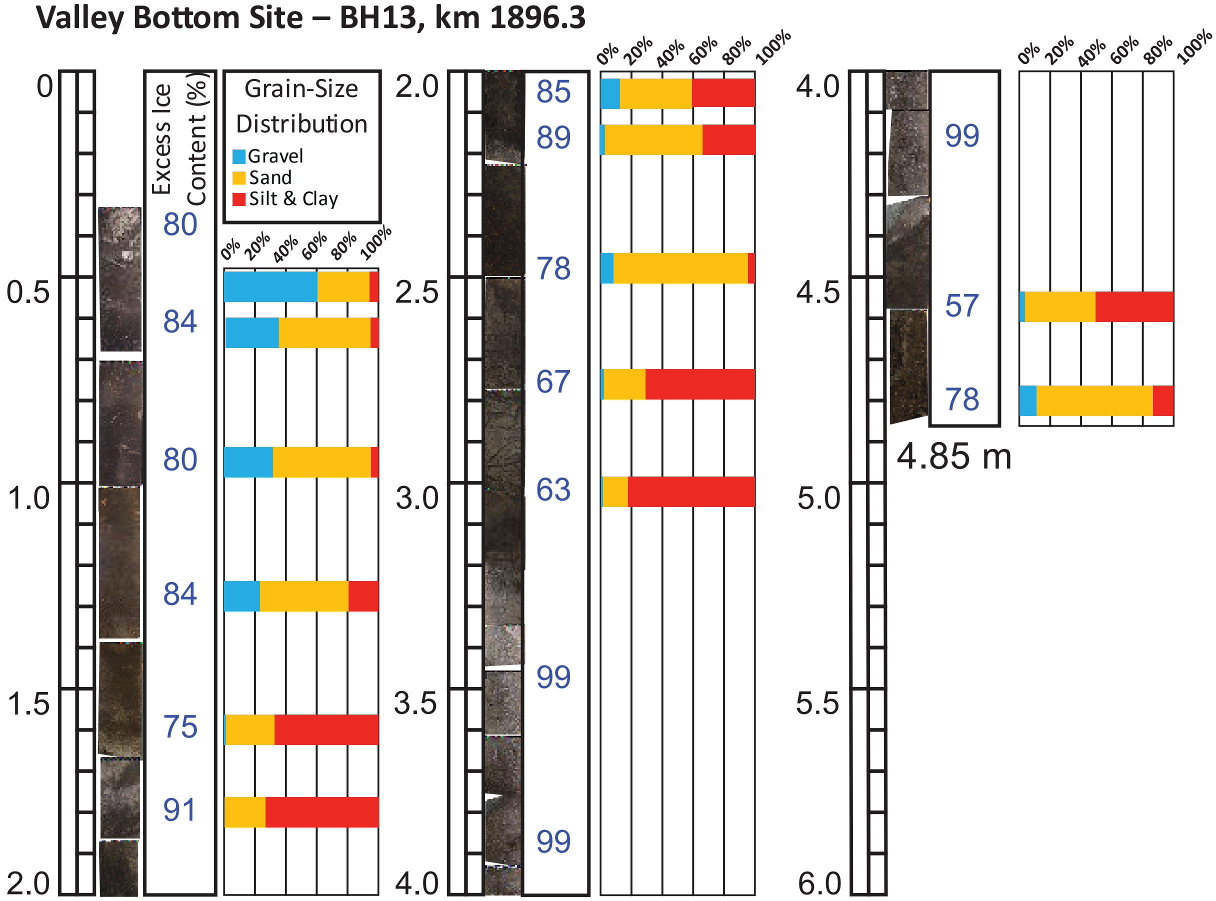


Figure 4.4.2. Log of borehole BH13.

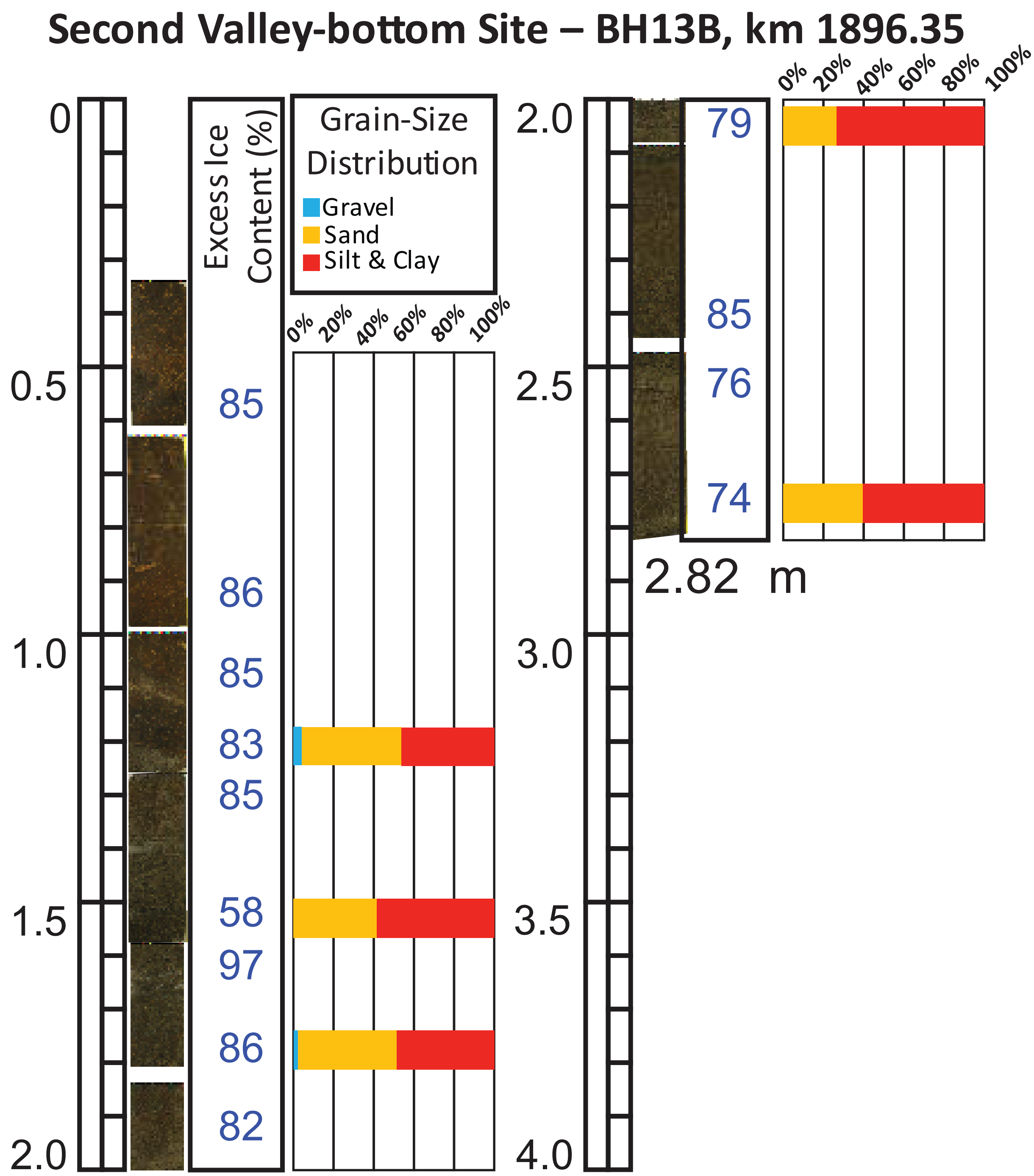


Figure 4.4.3. Log of borehole BH13b.

SUBSURFACE EXPLORATION AND TEST REPORT	**Alaska Highway - Site 6 - BH13 area**	SOURCE/TP#: **866-5307**
Boart Longyear	Establishment of Baseline Data, km 1897 LHS	PROJECT NO: 552-202021-0601-05-1
Sonic Drill	Coordinates: Z Nm Em	ELEVATION: m

SAMPLE TYPE: UNDISTURBED, DCPT, AUGER, BULK, SPT, CORE

SOIL DESCRIPTION	Depth (m)	SOIL DESCRIPTION	Depth (m)
ORGANICS -Black, fiberous, damp		-Dark brown -Less intense organic odour	
WELL-GRADED GRAVEL -Brown, free water, loose, angular	1		11
SILTY GRAVEL with SAND -Medium brown			
PEAT -Woody, partially decomposed, moist, black	2		12
ICE with ORGANIC SILT -Visible ice crystals (Vx), clear, white -Black, frozen bonded silt, organic odour -Random ice inclusions (Vr) -Clear, white, ~20%	3 4		13 14
SANDY ORGANIC SILT -Dark brown, frozen (Nbn) -Random ice formations (Vr) , clear, white ~5% -Trace gravel -Vx, black, <5%	5 6 7	SILT -Dark grey-brown -Vx, starts at 5% and increases with depth down to 18m, max 25%	15 16 17
ORGANIC SILT Dark grey, Nbe -Intense organic odour, some visible shell fragments	8	-Dark brown, Nbn - trace Vx	18
-Dark brown -Less intense organic odour	9		19
		END of HOLE	

Yukon Highways and Public Works
Transportation Engineering Branch

LOGGED BY: R.Stilwell	Termination Depth: 19.8m
COMPILED BY: R.Stilwell	Complete: 9/11/2015 2:00:00 PM
REVIEWED BY:	

Figure 4.4.4. Log of borehole HPW 866-5307.

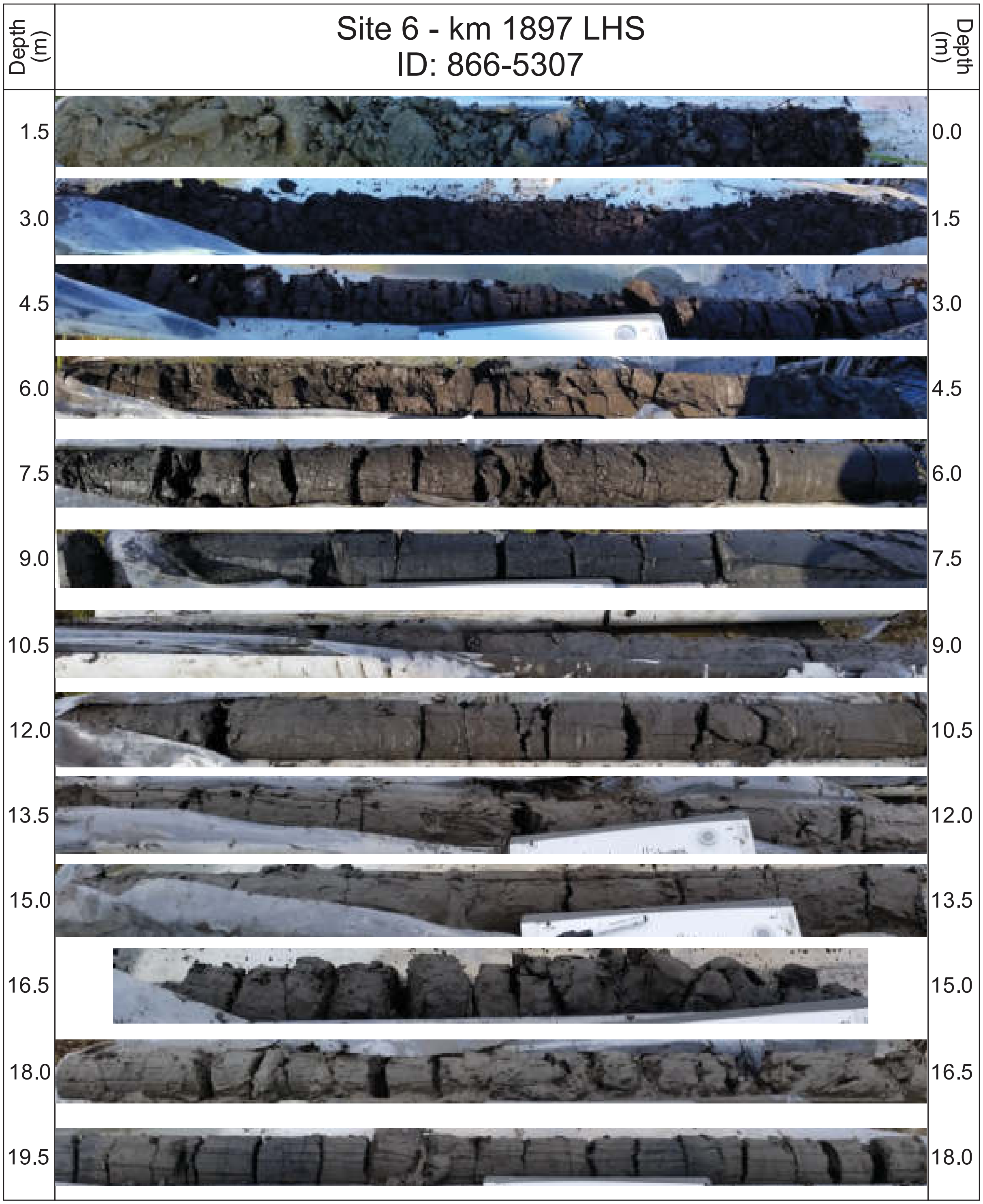


Figure 4.4.5. Cores collected from borehole HPW 866-5308

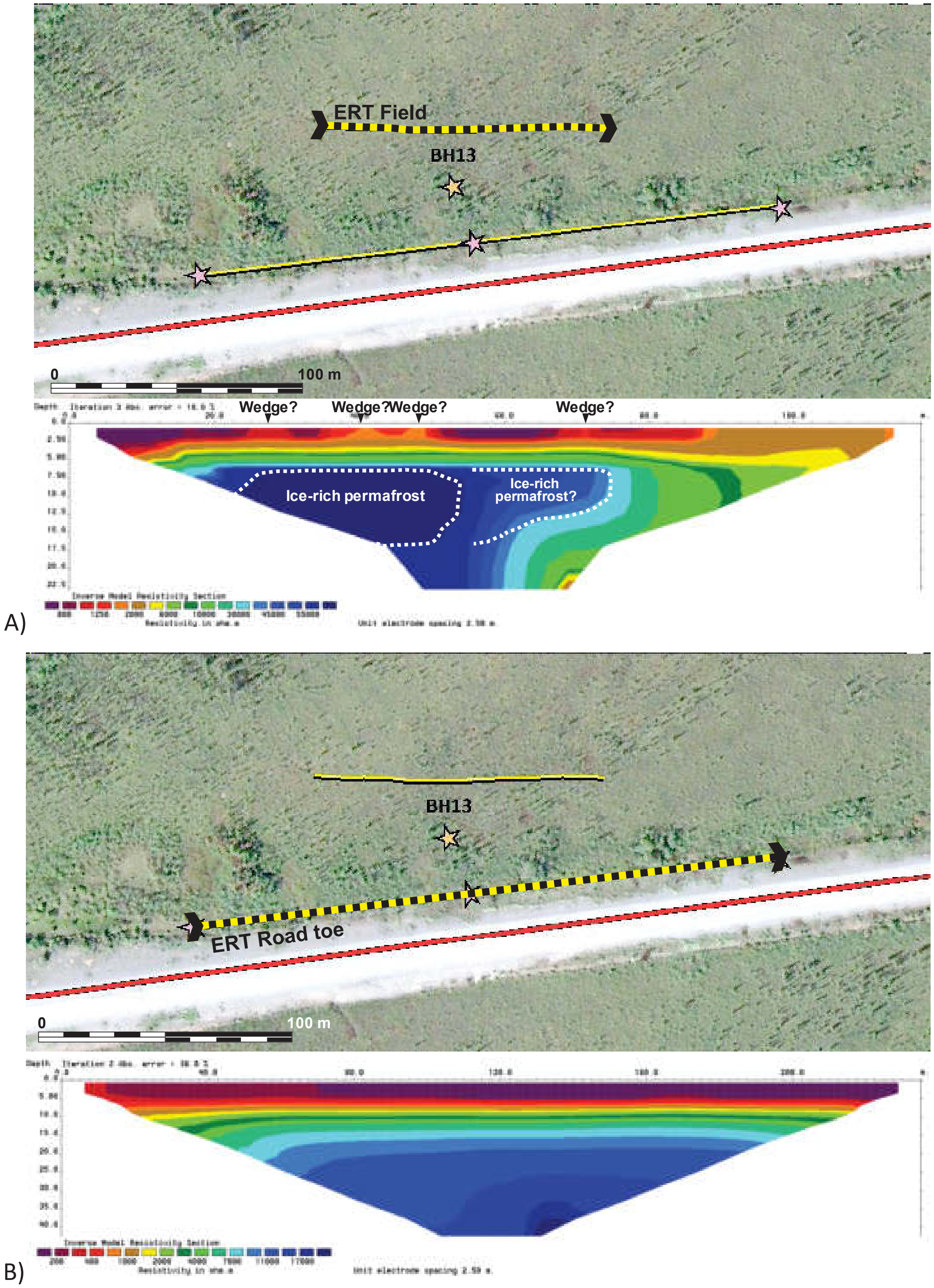


Figure 4.4.6. ERT Surveys performed at borehole BH13 for A) the field west of the BH13; and B) the toe of the highway embankment.

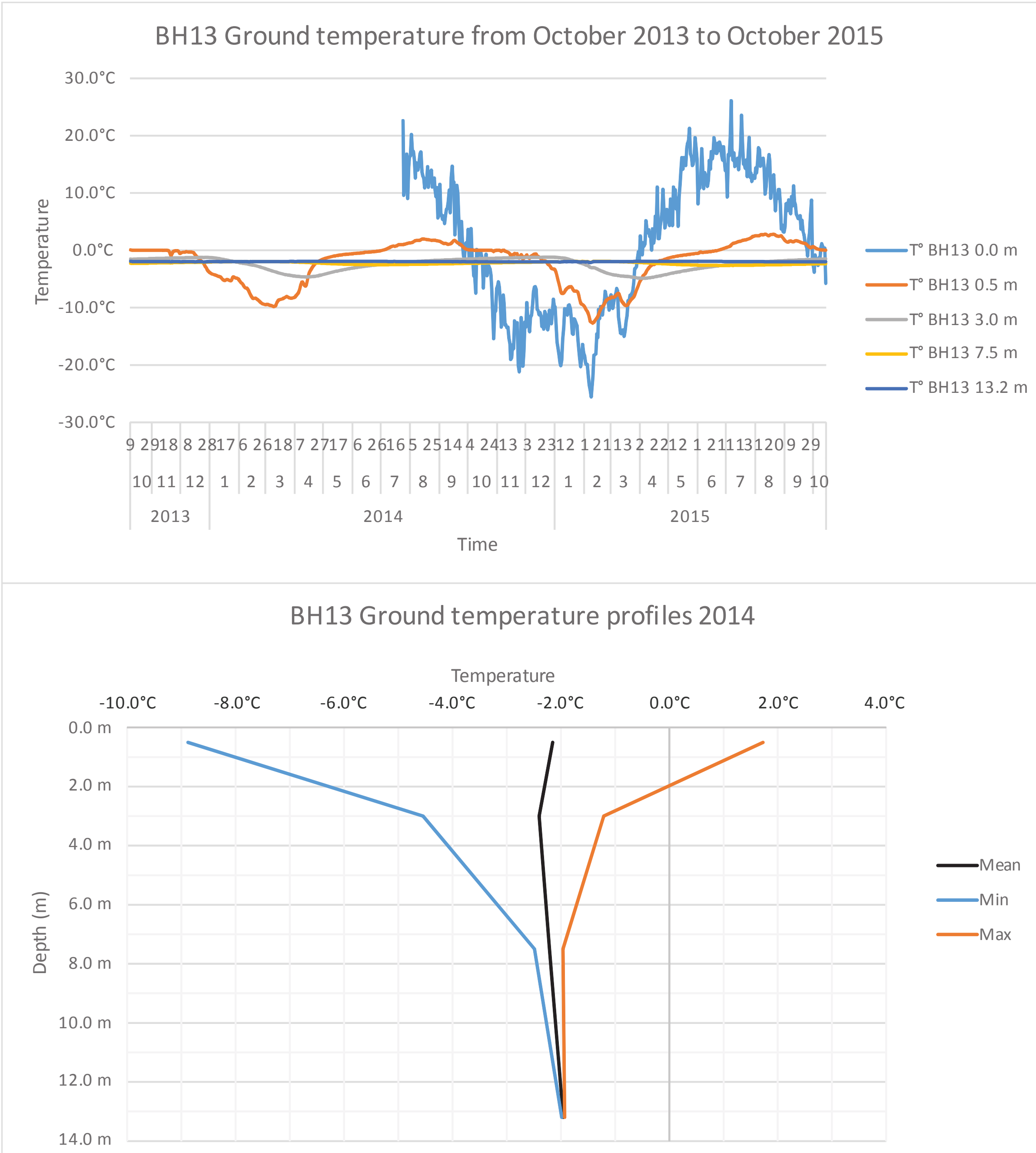


Figure 4.4.7. Ground temperature recorded in borehole BH13 from October 2013 to October 2015.

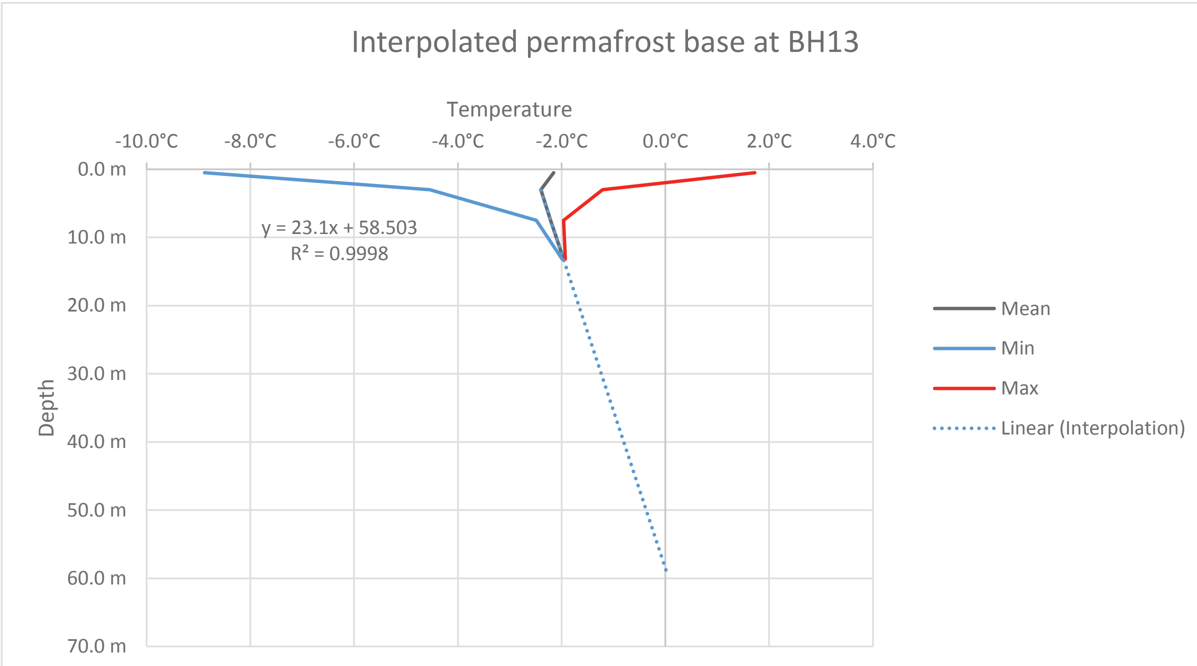


Figure 4.4.8. Interpolation of the permafrost base at BH13.

4.4.2 Adaptation design

4.4.2.1 Site configuration

The embankment cross section of this site is located at km 1896.3. As shown in Figure 4.4.9, the site has a straight segment of about 800 m between two large curves. The height of the embankment is approximately 2.5 m at the right side when facing north) and 2.0 m on the left side when facing north.

Two interceptor ditches have been dug about 10 m away from toe of the embankment on each side. Ditches only extend along the straight section of this road (Figure 4.4.10). The width and the height of both ditches are about 4 m and 1.5 m, respectively. Water was flowing in both ditches at the time of a site visit on October 15, 2015. The general topography of the terrain is relatively flat but the site crosses a valley between two hills. The general direction of the drainage crosses the road from left to right.

The areas between the toe of the embankment and the ditches are partly covered by grass, shrubs and other plants. Outside the ditches, the site is characterized by a higher concentration of trees and shrubs. The trees have lower density than the shrubs.

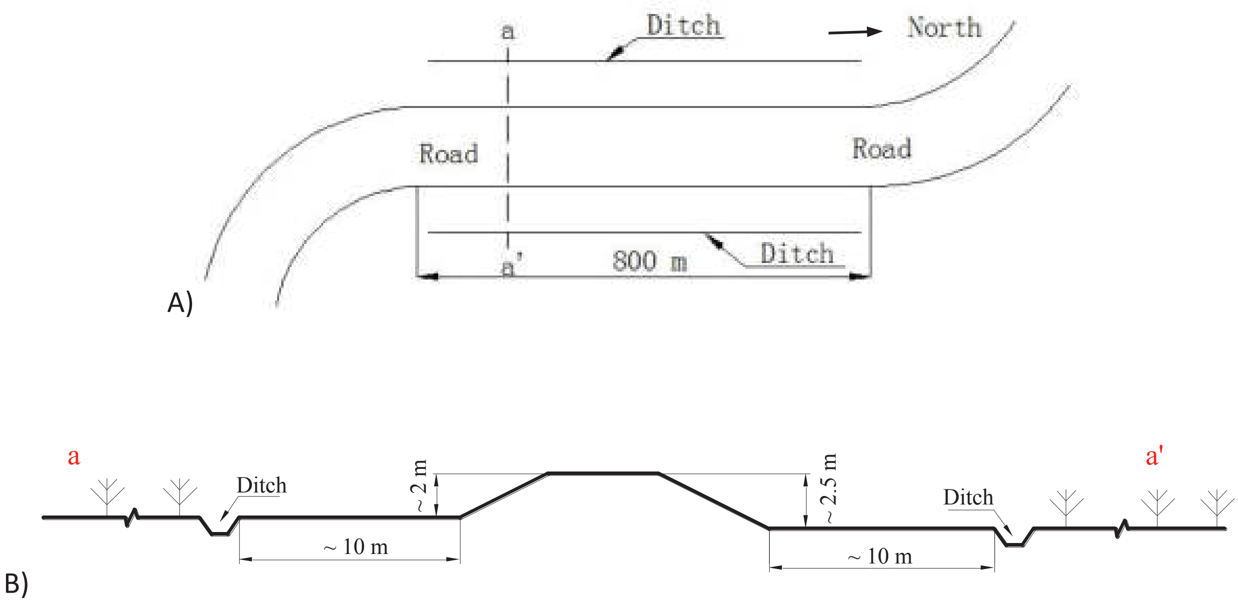


Figure 4.4.9. Schematic illustration of the field site A) Localisation of proposed embankment cross section in transverse profile; and B) a-a' embankment cross section km 1896.3

A)

B)

Figure 4.4.10 North to Beaver Creek adaptation site, km 1896 for A) Left side and right sides of the embankment, facing south; and B) Right side and left sides of the embankment, facing north.

4.4.2.2 Site thaw-sensitivity

Two NCE boreholes located in the field close to the embankment show high excess ice content. Whereas sand and silt are the main types of soil encountered, the maximum excess ice content can reach 99% as saturated frozen peat and ice wedges have been cored during the drilling. A third borehole drilled by HPW to a depth of about 20 m at the proposed embankment section shows silt as the main soil type, except gravel and peat in the upper 3.0 m. High ice content is reported from 2.9 m to about 4.6 m.

An ERT survey performed in the field suggests that ice-rich permafrost exists to depths of at least 16 m, and most likely deeper. The ground temperature recorded on site is -2.0 °C. Extrapolation of the ground temperature profile suggests that permafrost could be as thick as 58 m.

Consequently this site is located on relatively warm, ice-rich permafrost. This site will be prone to degradation exacerbated by climate warming and an expected increase of precipitation.

The detailed information about Site 4 is summarized in Table 4.4.2.

Table 4.4.2. Detailed information of site 4

Permafrost distribution (ice-rich) (Underground)	**Mean Annual Ground Temperature (°C)**	**Height Difference (m)**	
		Right Side	**Left Side**
3 m ~ more than 20 m	-2.0	2.0	2.5
Excess ice content (Maximum)	**Soil Types**	**Climate Warming (°C)**	
		2030s	**2050s**
99% (wege ice)	Mainly coarse-grained	1.5 to 2.0	2.5 to 4.5
Vegetation (Land Cover)	**Surficial Material**	**Drainage Condition**	
About 50%	Organic	Two Ditches	

4.4.2.3 Adaptation suitability

The permafrost for this section is relatively cold (-2.0 °C), well below the selection criteria of -1°C. Even if permafrost temperature provides a certain resilience, climate warming will affect the thermal stability of permafrost. Permafrost is also relatively thick (+50 m), and degradation may last for a long period of time. Excess ice content is important because of the presence of ice wedge complexes within the ground profile. For this site, there is a requirement to create stable thermal conditions in the short term and to compensate for the effect of climate warming to keep long-term thermal stability. The site is uniform, without notable curves or slopes. Due to its high thaw-sensitivity and favorable drainage condition, this site is a good candidate for adaptation.

4.4.2.4 Adaptation strategy

Based on the height requirements given in Section 3.2, the embankment is barely thick enough to allow for convective systems. ACE, HD and Air-Duct can thus be considered. However, it would be desirable to increase the thickness of the embankment to ensure a minimum thickness of 2.5 m.

Based on the considerations given in section 3.2 and local conditions, the following mitigation techniques are proposed for adaptation at site 4:

1. ACE placed on shoulder with HAS (Figure 4.4.11)
2. Insulation in shoulder with HAS (Figure 4.4.12)
3. HD in shoulder with HAS (Figure 4.4.13)

The adapted section extends from km 1896.0 to 1896.8 for a length of 800 m.

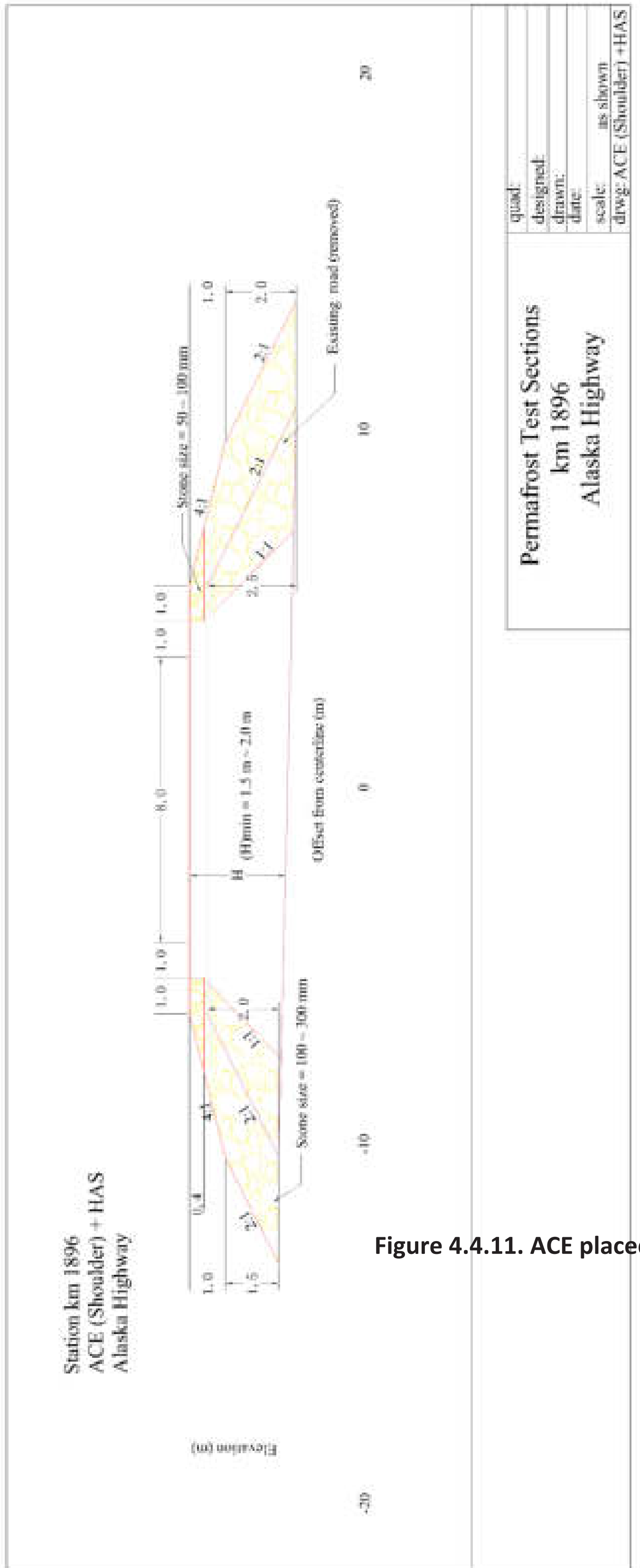
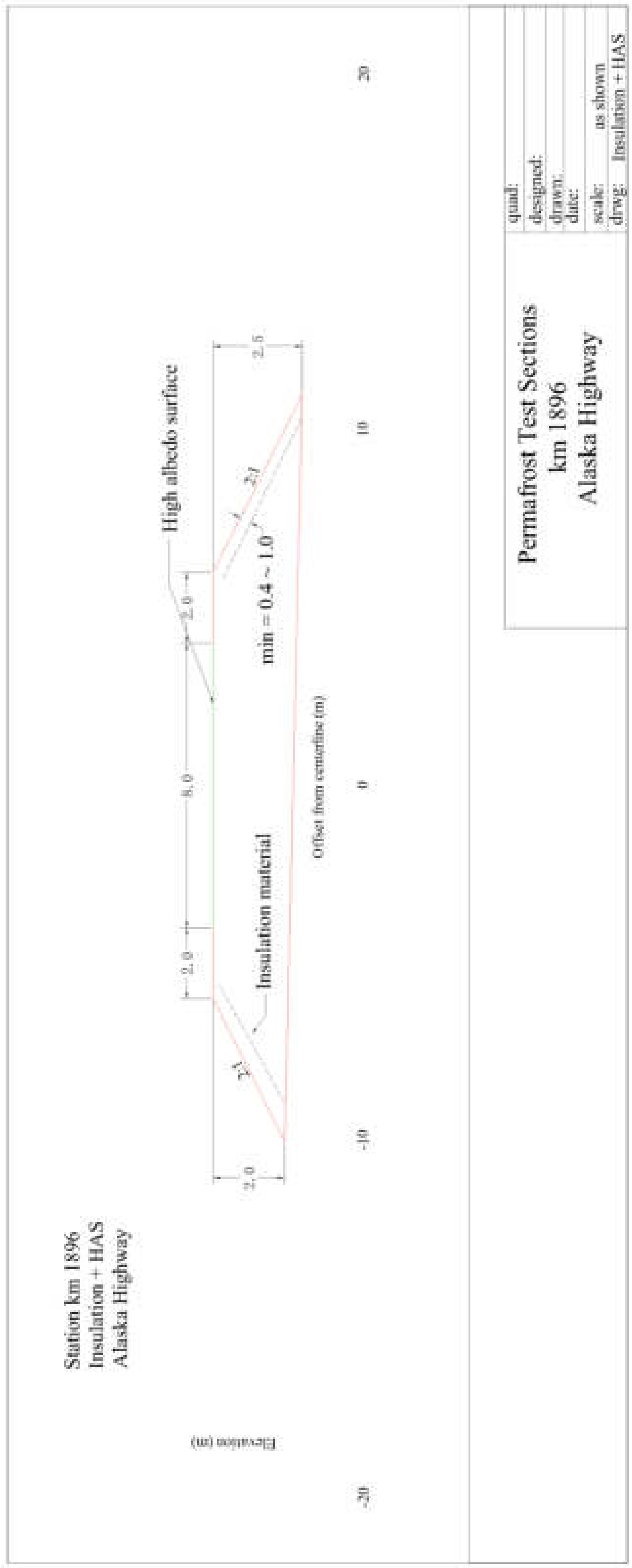


Figure 4.4.11. ACE placed on shoulder with HAS



n shoulder with HAS

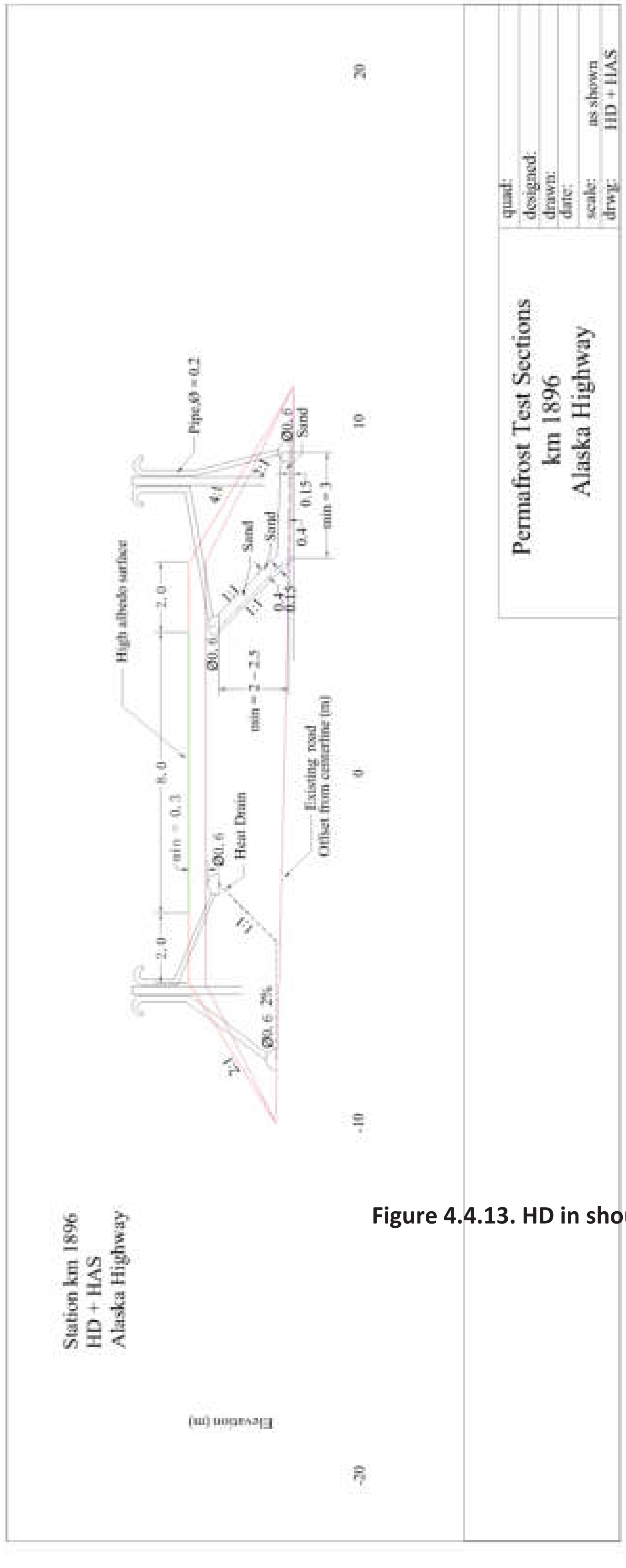


Figure 4.4.13. HD in shoulder with HAS

4.5 ADAPTATION SITE 5: MIRROR CREEK, BH11, KM 1886

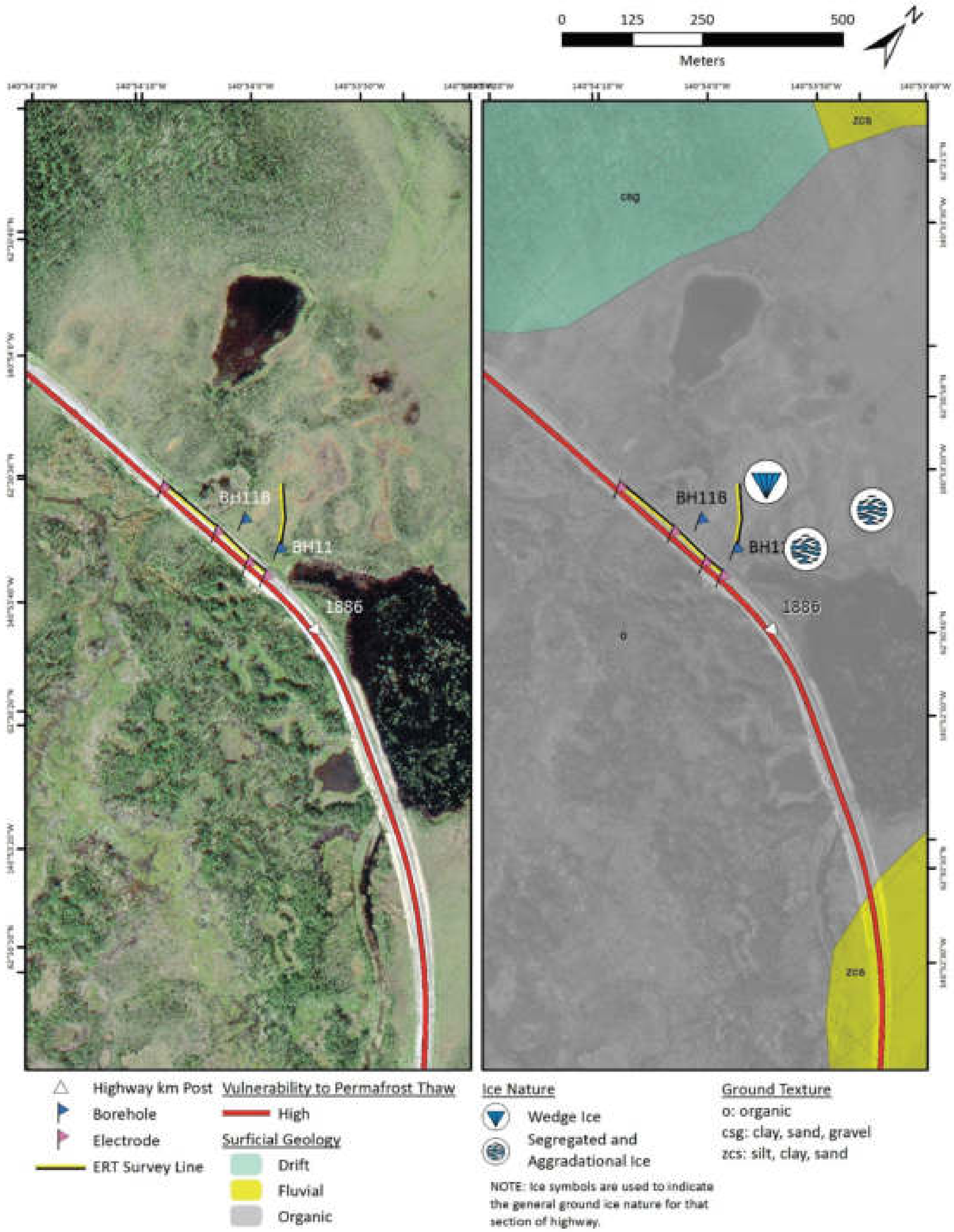


Figure 4.5.1. Vulnerability maps of Site 5 (satellite imagery and surficial geology)

4.5.1 Surficial geology and permafrost characterisation

- This highway section is underlain by relatively resilient permafrost (-1.5°C).
- The section crosses organic soils that are highly vulnerable to thaw settlement. Ice-rich permafrost can be expected as deep as 15 m or more.

4.5.1.1 Geology

This section of the road crosses terrain that was not glaciated during the McConnell glaciation. It crosses organic sediment and is surrounded by various surficial geology units including glacial (drift and moraine) and fluvial (Figure 4.5.1).

This section is located at a low elevation in a valley where organic soils have developed. Thermal properties of the organic material have favoured development of ice-rich permafrost. Wetlands have provided water that supports the growth of segregated ice and the formation of frost mounds. Extensive thermokarst processes, including pond and lake formation, are occurring near the road.

Drift materials are located northwest of the studied section. Drift deposits generally contain finer sediments than moraine deposits, therefore, it might be considered more thaw-sensitive than other glacial deposits. However, drift is still coarser, less frost-susceptible than other deposits, so its overall thaw vulnerability can be considered to be relatively low.

A fluvial complex consisting of silt and clay is located right hand side of the section. The fluvial complex is also covered by organic sediment in depressions and in wet conditions. Fluvial units are problematic when combined with the organic units. Fluvial deposits are fine grained, thick, and often ice-rich due to their frost-susceptibility, at least in the first metres of the profile. Organics overlie fluvial or glaciofluvial deposits in poorly drained areas.

4.5.1.2 Permafrost

This section of the highway crosses thaw-sensitive permafrost. Figures 4.5.2 and 4.5.3 present the logs of borehole BH11a and BH11b, respectively. Figure 4.5.4 and 4.5.5 shows the log and the pictures of the core, respectively, for borehole HPW 866-5309 which was drilled at the toe of the embankment.

Borehole BH11a was drilled in the field on a frost mound close to a lake. Silty sand was logged from the surface down to the depth of about 2 m, then sandy silt is found down to about 3.5 m. Finally, the soil grades to coarser sediment from sand to gravelly sand at 5.9 m, the end of the sampled borehole. Excess ice content can be as high as 85%, consisting of segregated ice. Borehole BH11b was drilled in the field in a drier environment. The stratigraphy shows sandy silt down to 2 m followed by silty sand down to 3.42 m, the end of the cored drilling. Excess ice content is lower than that at BH11a, with a maximum of 50%, but like BH11a, it also contains segregated ice. Both boreholes BH11a and BH11b where deepened with a water jet drill; in BH11b, the drilling slowed down at about 5 m, indicating likely ice-rich levels. After drilling deeper using water jet drilling, the final depths of borehole BH11a and BH11b were 8.5 m and 10.4 m, respectively. The log of HPW 866-5309 reports similar stratigraphy with silty ice-rich sediment down to about 6 m, then grading in coarser sand sediment. A significant gravelly fraction (~30-45%) appears at about 11.5 m depth and continues until the end of the borehole at 19.8 m. The log reports several lifts of ice-rich soil. Ice was reported from 0.3 to 6 m, and at about 10 m. From 10 to 19.8 m, less ice was observed.

Two ERT surveys where performed at the site; one in the field, starting from the frost mound at BH11a and ending in the open field, and one along the embankment. Both surveys are shown in Figure 4.5.6. The survey performed in the field shows areas of high resistivity approximately between 2.5 m and 11-13 m depth. Based on borehole observations, these highly resistive values likely represent ice-rich, relatively fine-grained material. While no wedge ice was clearly reported, observations in the area suggest the possibility of ice wedge complexes between about 5 and 15 m depth. The survey made along the embankment is inconclusive, showing highly resistive material below 10 m, which contradict boreholes observation. Yet it suggests a thermal effect of ponding water on the northern side of the survey.

Ground temperatures were recorded at borehole BH11a and BH11b that were drilled to a depth of 8.5 and 10.4 m, respectively, with a water jet drill. BH11a was instrumented with one 4-channel logger in October 2013 and BH11b was instrumented with two 4-channel loggers in May 2015 to allow ground temperature measurement at 4 and 8 different depths, respectively. The mean monthly ground temperature for the recording periods are presented in Table 4.5.1 A and 4.5.1 B, while ground temperature curves and profiles are shown in Figures 4.5.7 and 4.5.8 for each borehole. Permafrost appears to be relatively resilient with temperatures of -1.4°C and -1.5°C at depths of 8.5 and 10.4 m for BH11a and BH11b, respectively. Using the temperature profile in October 2015 from BH11b, the base of the permafrost can be tentatively extrapolated to a depth of about 46 m based on the thermal gradient of +0.1°C per 2.4 m, between 8 and 10.4 m. An extrapolation made on 2014 mean annual ground temperature curve from 3 to 8.5 m lead to a permafrost base located at 42.5 m (Figure 4.5.9).

Table 4.5.1 A. Ground temperature recorded at BH11a

	0.0 m	0.5 m	3.0 m	5.0 m	8.5 m
2013					
October		0.0°C	-1.2°C	-1.6°C	-1.6°C
November		0.0°C	-1.1°C	-1.5°C	-1.6°C
December		-0.1°C	-1.0°C	-1.4°C	-1.5°C
2014					
January		-2.4°C	-1.1°C	-1.3°C	-1.5°C
February		-5.3°C	-1.6°C	-1.4°C	-1.4°C
March		-6.9°C	-2.6°C	-1.5°C	-1.4°C
April		-4.7°C	-3.3°C	-1.9°C	-1.4°C
May		-0.9°C	-2.8°C	-2.2°C	-1.5°C
June		0.1°C	-2.1°C	-2.1°C	-1.6°C
July	13.3°C	2.8°C	-1.7°C	-2.0°C	-1.6°C
August	13.5°C	3.4°C	-1.4°C	-1.8°C	-1.6°C
September	5.2°C	1.6°C	-1.3°C	-1.7°C	-1.6°C
October	-3.7°C	0.0°C	-1.1°C	-1.5°C	-1.6°C
November	-12.9°C	0.0°C	-1.0°C	-1.4°C	-1.5°C
December	-15.8°C	-0.3°C	-0.9°C	-1.4°C	-1.5°C
2015					
January	-21.0°C	-4.4°C	-1.0°C	-1.3°C	-1.5°C
February	-20.4°C	-9.4°C	-2.1°C	-1.3°C	-1.4°C
March	-12.8°C	-7.4°C	-3.3°C	-1.7°C	-1.4°C
April	1.4°C	-3.7°C	-3.7°C	-2.2°C	-1.4°C
May	12.8°C	-0.9°C	-3.0°C	-2.4°C	-1.5°C
June	15.5°C	0.7°C	-2.2°C	-2.3°C	-1.6°C
July	15.9°C	4.1°C	-1.8°C	-2.1°C	-1.7°C
August		3.9°C	-1.5°C	-1.9°C	-1.7°C
September		1.7°C	-1.3°C	-1.7°C	-1.7°C
October		0.2°C	-1.2°C	-1.6°C	-1.6°C

Table 4.4.1 B. Ground temperature recorded at BH11b

	0 m	0.5 m	1.5 m	3 m	4 m	6 m	8 m	10.4 m
2015								
June	14.9°C	2.2°C	0.7°C	0.6°C	0.4°C	-1.0°C	0.2°C	0.1°C
July	15.3°C	4.0°C	-0.1°C	-0.4°C	-1.5°C	-1.8°C	-1.5°C	-1.4°C
August	10.8°C	4.0°C	-0.4°C	-1.2°C	-1.6°C	-1.7°C	-1.7°C	-1.5°C
September	5.0°C	1.9°C	-0.3°C	-1.0°C	-1.4°C	-1.6°C	-1.7°C	-1.5°C
October	-1.3°C	0.2°C	-0.2°C	-0.9°C	-1.3°C	-1.5°C	-1.6°C	-1.5°C

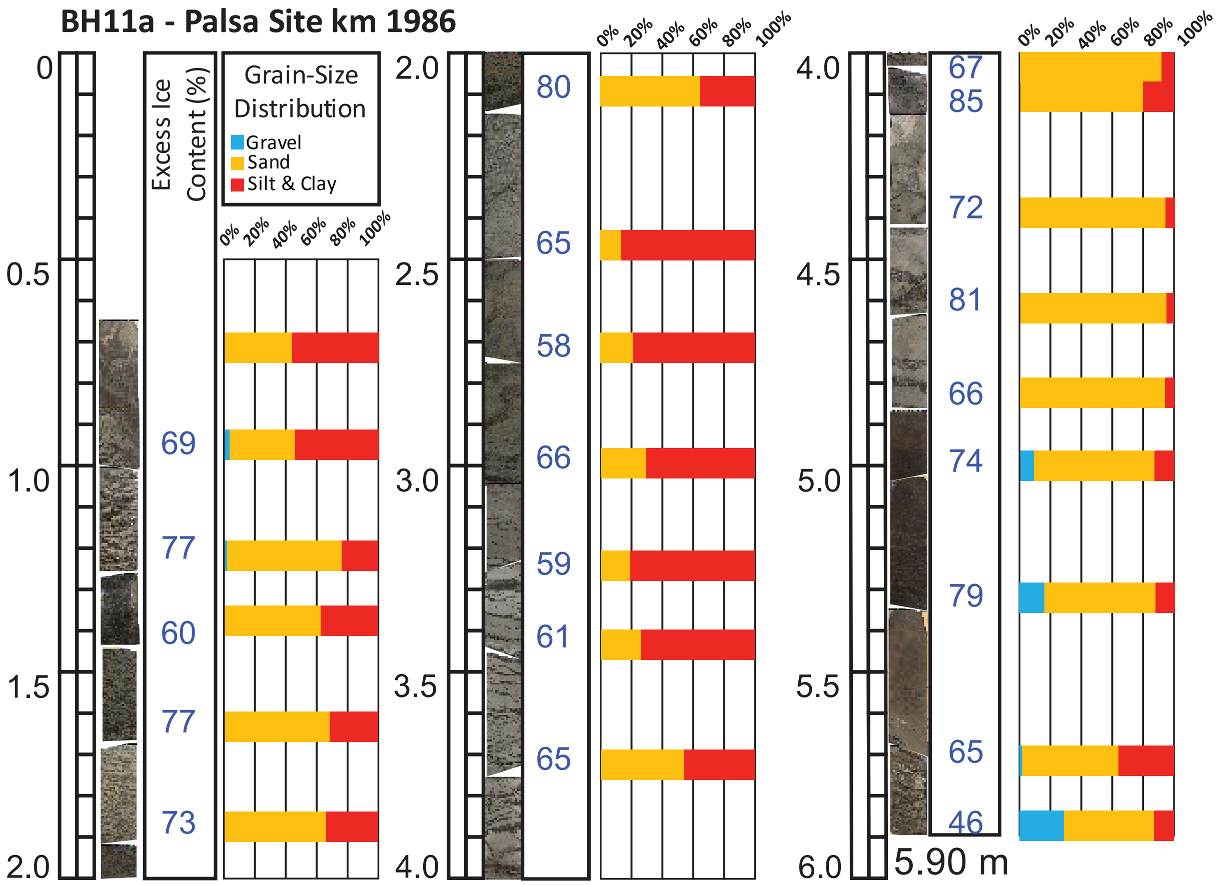


Figure 4.5.2. Log of borehole BH11a.

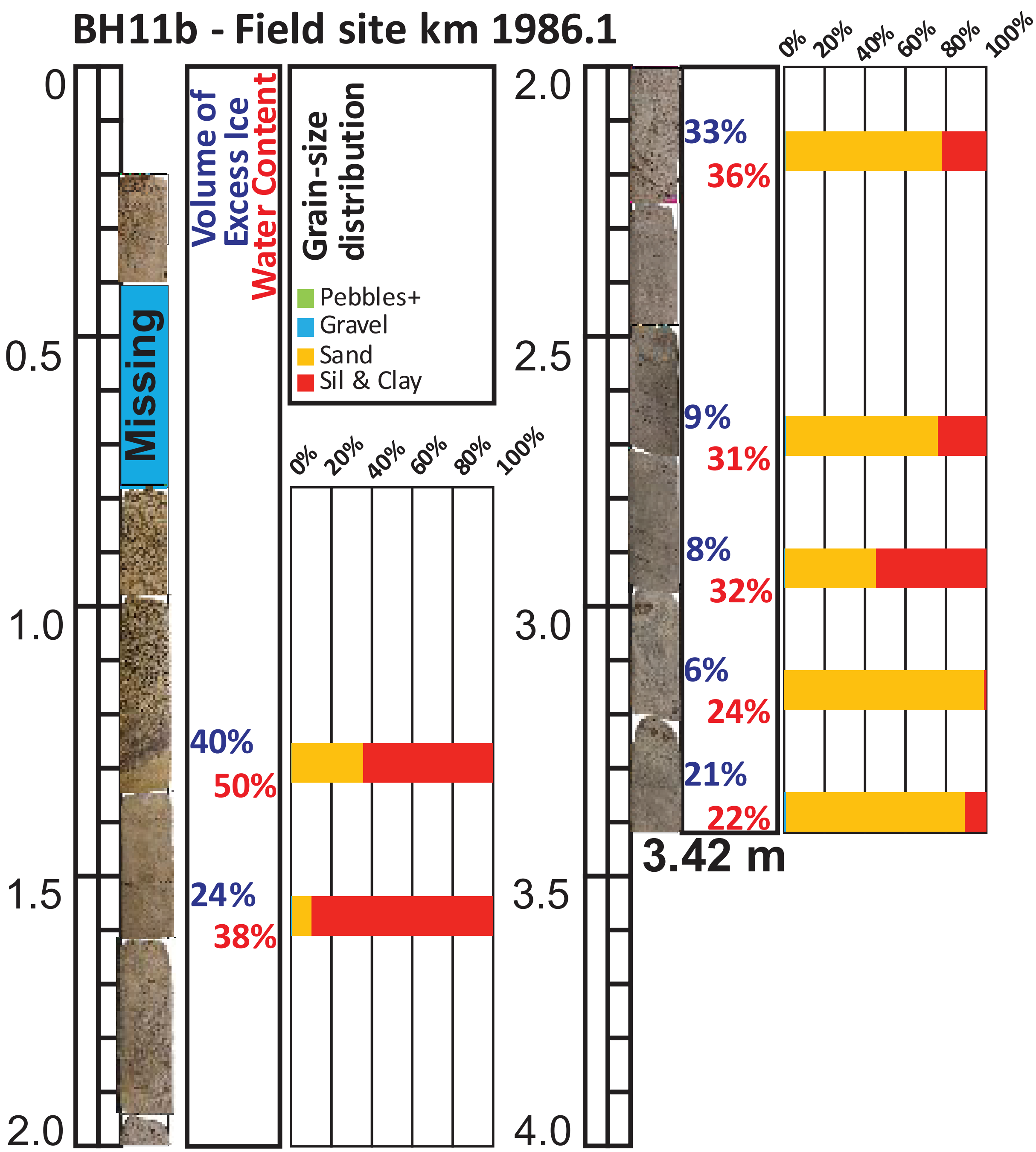


Figure 4.5.3. Log of borehole BH11b.

SUBSURFACE EXPLORATION AND TEST REPORT	**Alaska Highway - Site 4 - BH11 area**	SOURCE/TP#: **866-5309**
Boart Longyear	Establishment of Baseline Data, km 1886 RHS	PROJECT NO: 552-202021-0601-05-1
Sonic Drill	Coordinates: Z Nm Em	ELEVATION: m

SAMPLE TYPE: UNDISTURBED, DCPT, AUGER, BULK, SPT, CORE

SOIL DESCRIPTION	Depth (m)
PEAT -Mixture of fiberous and woody	
ICE and PEAT -Vx ICE and ORGANIC SILT -Vs, 50% ice -White, clear ice, brown silt	1
ICE and SILT -60-70% Ice -Crystaline, clear, white, highly fractured -Grey silt	2
	3
<<L>- Organic silt seam ICE with SILT and SAND -Clear, white, granular, highly fractured	4
SANDY SILT with ICE -VxVr, 20% Ice	5
	6
WELL-GRADED SAND with SILT -Medium grained, dark grey -Frozen Nbn	7
POORLY GRADED SAND -Coarse grained -10% Vc	8
-Grey -Vc, ~1mm coating	9
ICE and SILT -60% ice, clear, white, square crystals	

SOIL DESCRIPTION	Depth (m)
SILT -Grey, Nbn	
WELL-GRADED SAND with SILT and GRAVEL -rounded -Vc -rounded	11
-Nbn	12
	13
-Medium grey, Nbe	14
	15
SILTY SAND with GRAVEL -Thawed due to drill action	16
	17
WELL GRADED GRAVEL with SILT and SAND	18
	19
END of HOLE	

Yukon — Highways and Public Works, Transportation Engineering Branch

LOGGED BY: R.Stilwell	Termination Depth: 19.8m
COMPILED BY: R.Stilwell	Complete: 9/12/2015
REVIEWED BY:	

Figure 4.5.4. Log of borehole HPW 866-5309

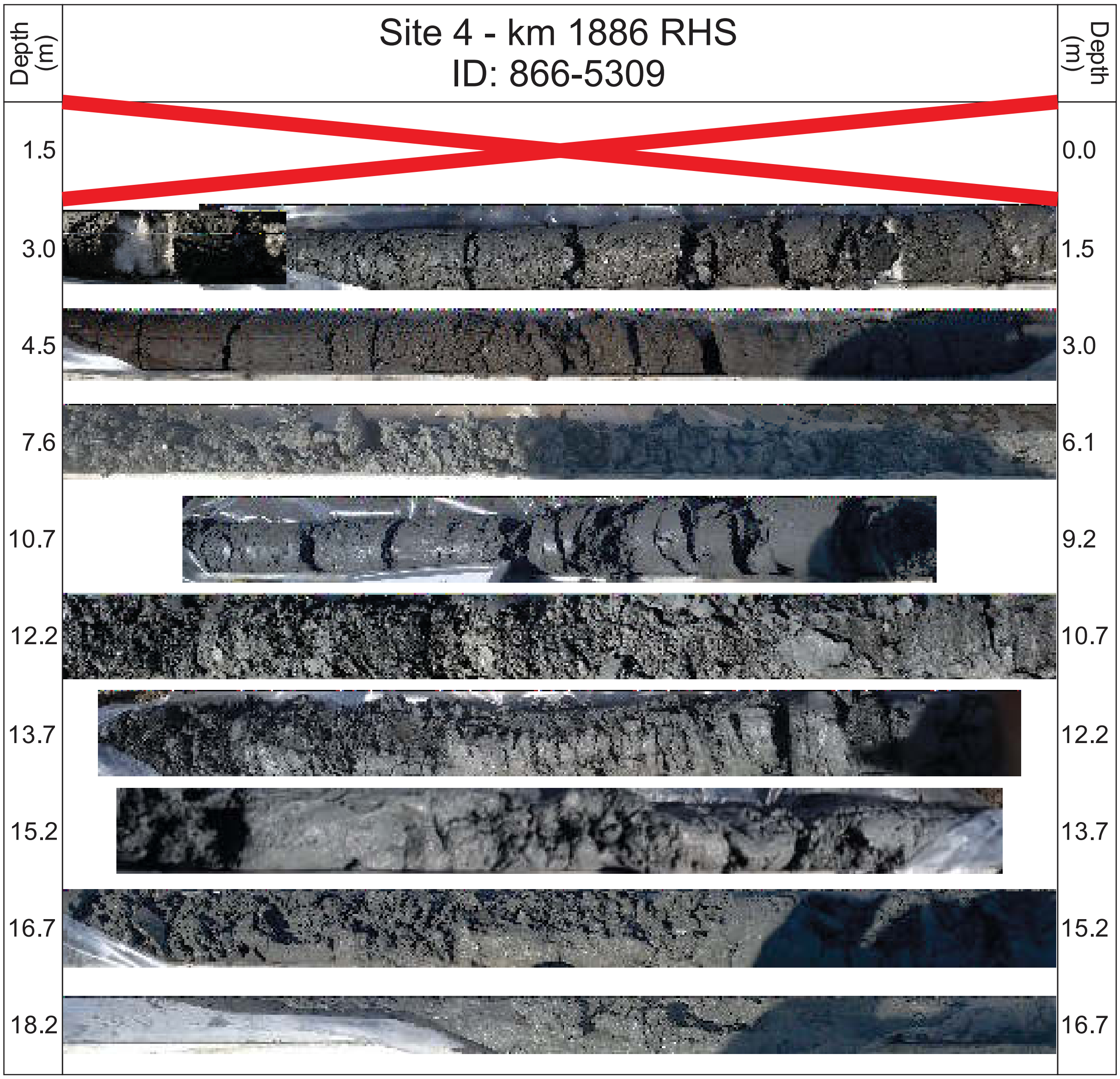
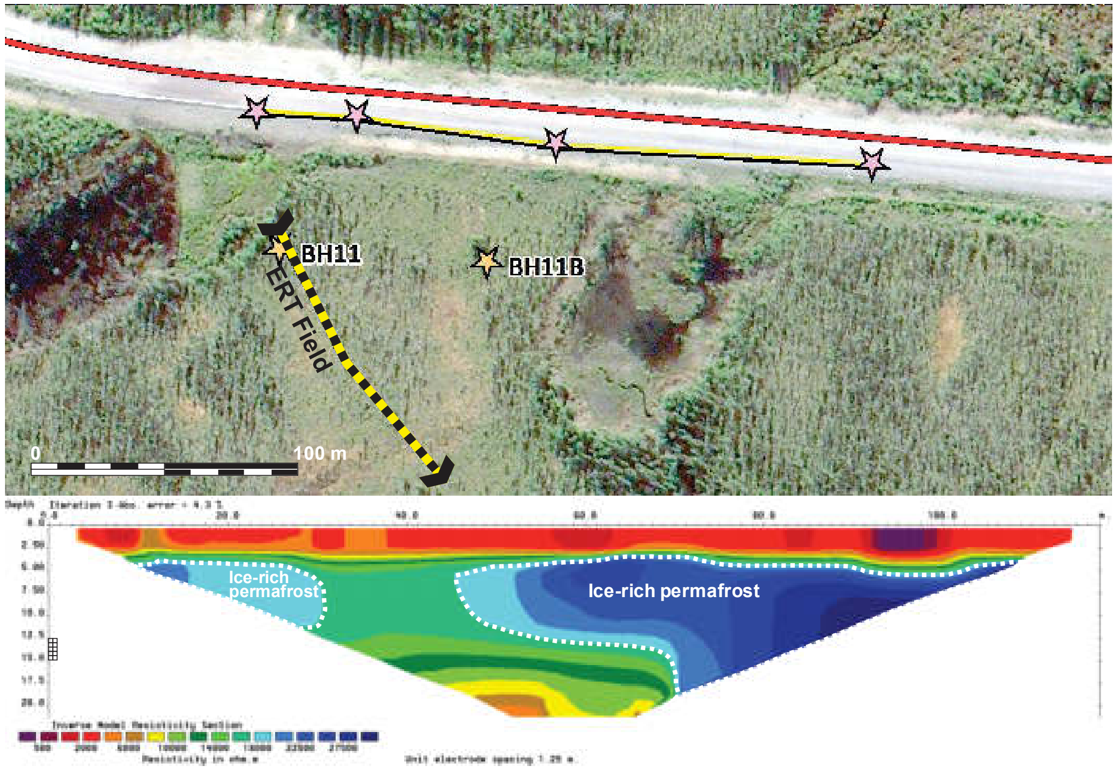
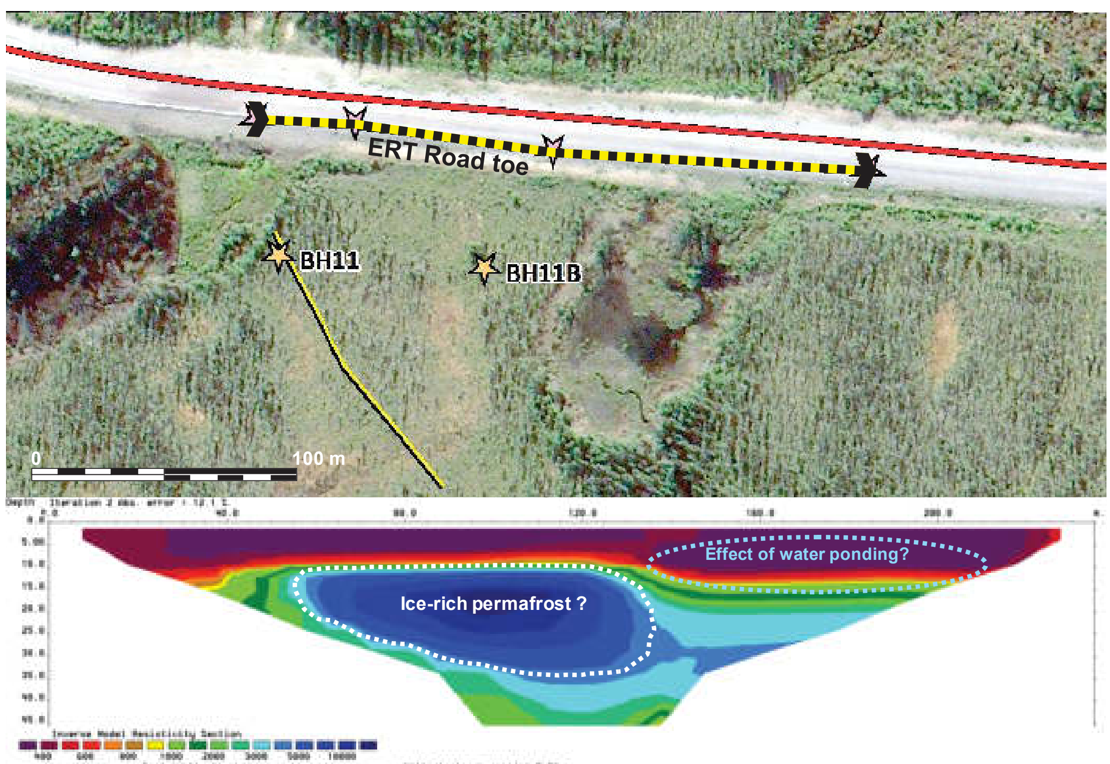


Figure 4.5.5. Cores collected from borehole HPW 866-5310



A)



B)

Figure 4.5.6. ERT Surveys performed at site of BH11 for A) the field; and B) the toe of the highway embankment.

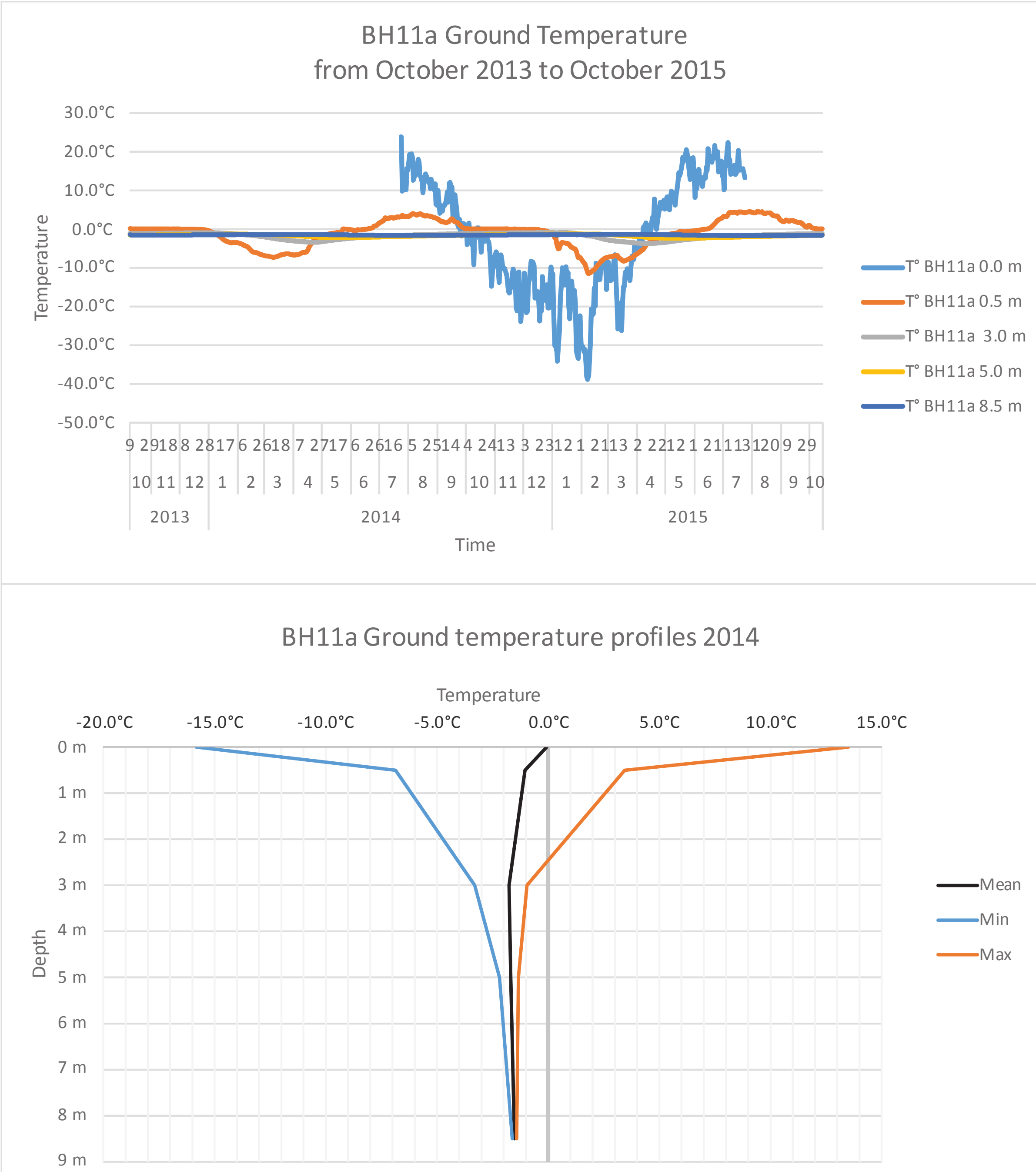


Figure 4.5.7. Ground temperature recorded in BH11a from October 2013 to October 2015.

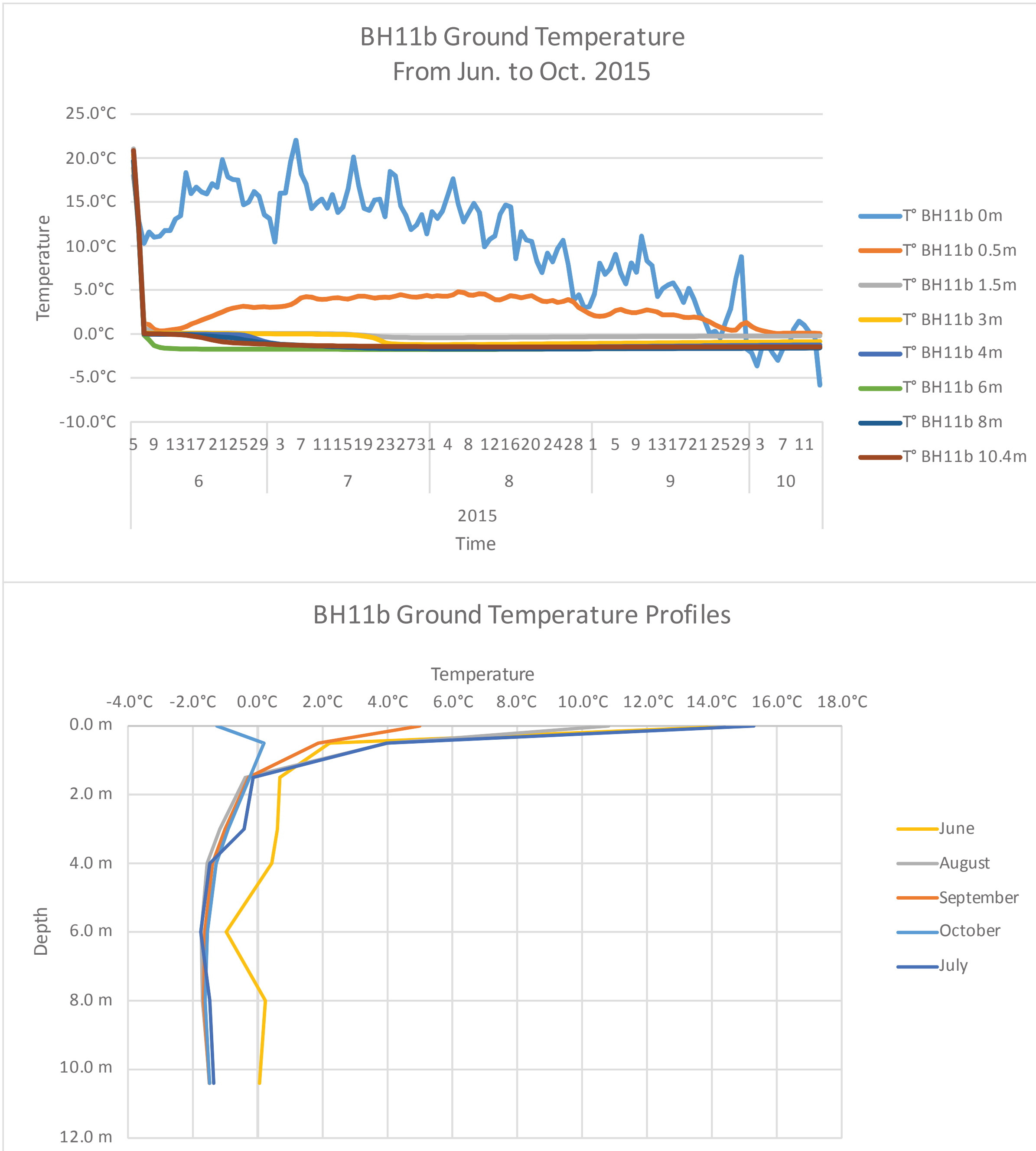


Figure 4.5.8. Ground temperature recorded in BH11b from June 2015 to October 2015.

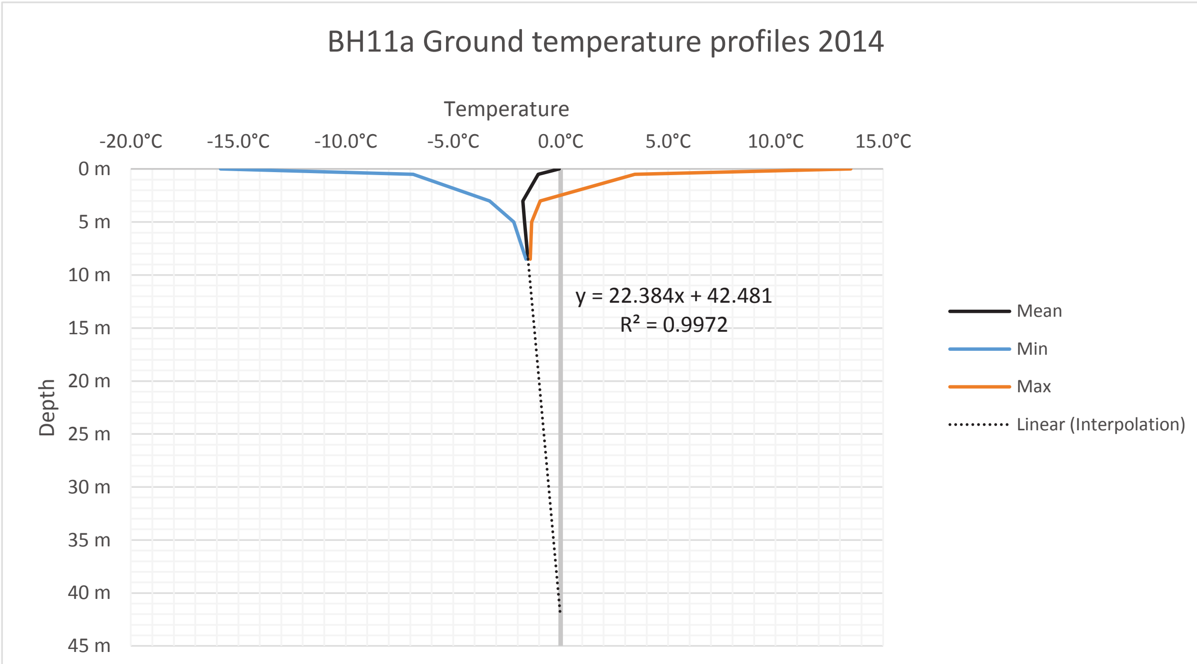


Figure 4.5.9. Interpolation of the permafrost base at BH11a

4.5.2 Adaptation design

4.5.2.1 Site configuration

This site is located north of Beaver Creek, 2 km after Mirror Creek Bridge at km 1886.1. The road crosses some organic rich soil overlaying fluvial deposits (sandy and silty sediment). The proposed adaptation site is located at km 1886.2, and is shown in Figure 4.5.10. The section is straight and 1-km long between two wide curves. The terrain is relatively flat but surrounded by hills on right hand side.

As shown in Figure 4.5.10, the embankment height varies approximately between 2.5 m at right hand side and 2.8 m at the left hand side. There are no ditches on either side of the road. A large culvert, replaced in 2014, passes under the road. The area is very wet; a large thermokarst lake is present at the east end curve of the section, close to the right hand side (when facing north). Another smaller pond (not shown in the figure) is present at km 1886.2, also on the right hand side.

Bogs are present along the left side, they developed in the meanders of a relict fluvial system. Most of the terrain of this site is covered by vegetation, except in the areas along the road where sparse grass and shrubs can be observed (Figure 3.5.11).

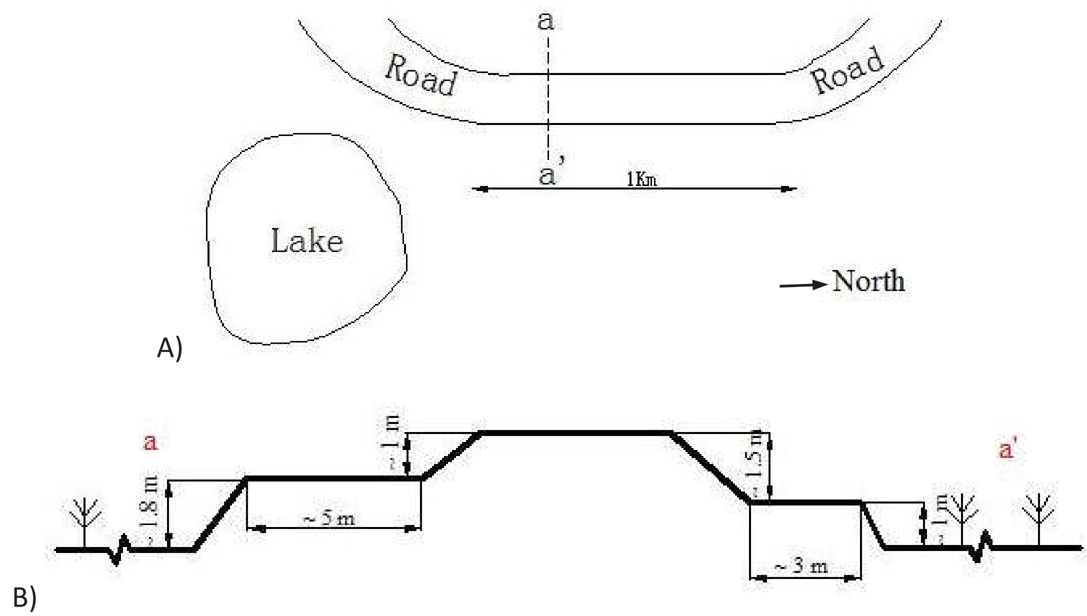


Figure 4.5.10. Schematic illustration of the Mirror Creek adaptation site A) Localisation of proposed embankment cross section in transverse profile; and B) a-a' embankment cross section, km 1886.1

A) 

B) 

Figure 3.5.11 Mirror Creek adaptation site, km 1886 for A) Right side of the embankment, facing south; and B) Left and right sides of the embankment, facing north.

4.5.2.2 Site thaw-senstivity

The NCE boreholes located in the field at the right hand side of the embankment cross section, as well as the HPW borehole located closer to the road also at the right hand side, show excess ice content as high as 70%, mostly associated with silt and organic rich soil. Excess ice content is concentrated in the first 10 m of the profile. The excess ice content decreases as the sediment becomes coarser with depth.

An ERT survey conducted in the field suggest that ice-rich permafrost may extend as deep as 15 m, and possibly deeper. The local context and aerial imagery suggest the presence of ice wedge complexes.

The ground temperature is about -1.5 °C, which is relatively warm. Climate warming can disrupt the thermal equilibrium, and will impact the warm, ice-rich permafrost with projected temperature increases of 1.5-2.5°C by the 2030s and 2.5-4.0°C by the 2050s. Moreover, the expected increase of precipitation can lead to higher water levels in the surrounding wetlands. Permafrost in this area tends to degrade faster than it does in other places along this Alaska Highway, due to the presence of the wetlands. The site is located in an extensive thermokarst area and is highly vulnerable to permafrost thaw. To summarize, at this site, the permafrost is ice-rich, relatively thick and warm, and highly thaw-sensitive.

The detailed information about adaptation Site 5 is summarized in Table 4.5.2.

Table 4.5.2. Detailed information of adaptation Site 5.

Permafrost distribution (ice-rich) (Underground)	**MAGT (°C)**	**Height Difference (m)**	
		Right Side	**Left Side**
3 m ~ more than 20 m	-1.5	2.5	2.8
Excess ice content (Maximum)	**Soil Types**	**Climate Warming(°C)**	
		2030s	**2050s**
69%, and possible ice wedge	Mainly fine-grained	1.5 ~ 2.5	2.5 ~ 4.0
Vegetation (Land Cover)	**Surficial Material**	**Drainage Condition**	
About 90%	Organic on fluvial	One lake nearby	

4.5.3 Adaptation suitability

Many of the criteria to apply mitigation techniques that are described at the beginning of Section 3 apply to Site 5. Permafrost has a temperature below -1°C, the excess ice content exceeds 40%, and the base of permafrost is located deeper that 20 m. Also, the section is on tangent, without horizontal and vertical curves. However, the presence of significant lateral water flows and the presence of substantial water bodies near the site may eliminate the effect of thermal stabilisation techniques. As a result, this site is not recommended for the application of a thermal stabilisation technique.

4.6 ADAPTATION SITE 6: U.S. BORDER, BH12, KM 1894

Figure 4.6.1. Vulnerability maps of Site 6 (satellite imagery and surficial geology)

4.6.1 Surficial geology and permafrost characterisation

- This highway section is underlain by thermally resilient permafrost (approximately -3°C).
- Highway sections cross fluvial units that are highly vulnerable to thaw settlement. Ice-rich permafrost can be expected as deep as 20–25 m. The permafrost base could be as deep as 60 m.

4.6.1.1 Geology

This section of the road goes through a valley between two hills. It is on terrain that was not glaciated during the McConnell glaciation. Most of it crosses fluvial sediments, but it also encroaches on colluvium. The fluvial complex fills the valley bottom and consists of sand, silt and clay, whereas colluvium is present on the relief or close by. The colluvium is comprised of silt, sand and mixed fragments (Figure 4.6.1).

The fluvial material is the most problematic. These deposits are fine grained and thick. Air photos and field observation shows that they contain ice wedge networks. In addition, organic soils often overlie the fluvial deposits, which developed in poorly drained depressions. The thermal properties of the organic layer favoured deeper permafrost aggradation, and wetlands provide water that supports the growth of segregated ice. When the ice-wedges thaw, the resulting thermokarst processes cause water ponding, thermokarst lakes, and/or thermal erosion.

The colluvial deposits may also be thaw-sensitive, but their thickness can be assumed to be relatively limited because of their location on slopes. However, because the colluvium may overlie more sensitive material such as fluvial deposits, especially at the toe if the hills, slope movements and solifluction might cause problems for the road.

4.6.1.2 Permafrost

This section of the highway is built over thaw-sensitive permafrost. Figures 4.6.2, 4.6.3, and 4.6.4 present the logs of borehole BH12, at the bottom of the valley, BH12S, on the south side of the valley, and BH12N, on the north side of the valley, respectively. These boreholes were drilled in the field by NCE. Figure 4.6.5 and 4.6.6 show the log and the pictures of the core, respectively, for borehole HPW 866-5308. All three NCE boreholes show ice-rich fine-grained material. Sediment consists mostly of sandy silt and silty sand. Excess ice content can be as high as 85%, usually averaging ~60%. BH12S encountered an ice wedge at about 5.6 m depth. Ice wedges were also observed in the interceptor ditch excavated by HPW at km 1894 showing that they can be relatively close to the surface.

Alaska pipeline boreholes (unpublished) and stratigraphic sections 4-A07, 4-A08 and 4-A09 from the surficial geology map show that such ground ice can be encountered as deep as 20 m. The log of HPW 866-5308 reports similar stratigraphy with silty ice-rich sediment alternating with organic and organic-rich layers. Several ice-rich layers also are found at approximate depth of 10 m. Stratified ice, probably an ice wedge, is reported from 4.5 to 6 m. From 10 m, the sediment is almost pure silt with some traces of clay. While no significant amount of ground ice is present, water content remains relatively high between 21 and 47 %.

Two ERT surveys are shown in Figure 4.6.7; one in the field between BH12 and the road, and the other along the embankment. The survey performed in the field shows two areas of high resistivity. On the south side of the survey the area extends down to about 16 m, while on the north side it extends deeper than 20 m. It can be assumed, based on both borehole and field observations, that these highly resistive values represent the ice-rich levels, more likely ice-wedge formations. The survey made along the embankment shows no clear resistivity pattern, except possibly the thermal effect of a nearby creek.

Ground temperatures were recorded in borehole BH12 using a Campbell CR1000 connected to a thermistor string allowing ground temperature measurement at 11 different depths. Temperature has been monitored since August 2013. The mean monthly ground temperatures for the recording period are presented in Table 4.6.1, while ground temperature curves and profiles are shown in Figure 4.6.8. Permafrost appears to be cold; oscillating between -3.0 and -3.6°C at the depth of 9.5 m.

Table 4.6.1. Ground temperature recorded at BH12

	0.0 m	0.5 m	1.0 m	1.5 m	2.0 m	3.0 m	4.0 m	5.0 m	6.5 m	8.5 m	9.5 m
2013											
August	9.4°C	0.2°C	-0.9°C	-1.4°C	-1.8°C	-2.6°C	-3.1°C	-3.4°C	-3.6°C		-3.4°C
September	3.2°C	0.0°C	-0.7°C	-1.1°C	-1.5°C	-2.2°C	-2.7°C	-3.1°C	-3.4°C		-3.4°C
October	-0.6°C	-0.1°C	-0.6°C	-1.0°C	-1.3°C	-2.0°C	-2.4°C	-2.8°C	-3.2°C	-3.2°C	-3.3°C
November	-3.6°C	-0.2°C	-0.5°C	-0.9°C	-1.1°C	-1.8°C	-2.2°C	-2.6°C	-3.0°C	-3.1°C	-3.2°C
December	-6.4°C	-2.3°C	-1.7°C	-1.5°C	-1.4°C	-1.7°C	-2.1°C	-2.4°C	-2.8°C	-3.0°C	-3.1°C
2014											
January	-8.7°C	-6.6°C	-5.6°C	-4.6°C	-3.9°C	-2.9°C	-2.5°C	-2.5°C	-2.7°C	-2.9°C	-3.0°C
February	-11.7°C	-8.3°C	-7.0°C	-5.9°C	-5.2°C	-4.1°C	-3.4°C	-3.0°C	-2.8°C	-2.8°C	-3.0°C
March	-10.7°C	-9.1°C	-8.2°C	-7.3°C	-6.5°C	-5.2°C	-4.2°C	-3.6°C	-3.1°C	-2.9°C	-3.0°C
April	-1.9°C	-4.7°C	-5.7°C	-6.1°C	-6.1°C	-5.6°C	-4.8°C	-4.2°C	-3.5°C	-3.1°C	-3.0°C
May	4.7°C	-1.3°C	-2.4°C	-3.2°C	-3.8°C	-4.6°C	-4.6°C	-4.3°C	-3.8°C	-3.4°C	-3.2°C
June	7.9°C	-0.7°C	-1.5°C	-2.2°C	-2.7°C	-3.5°C	-3.9°C	-4.0°C	-3.9°C	-3.5°C	-3.3°C
July	10.8°C	-0.3°C	-1.1°C	-1.6°C	-2.0°C	-2.9°C	-3.3°C	-3.6°C	-3.7°C	-3.5°C	-3.4°C
August	9.8°C	0.2°C	-0.8°C	-1.2°C	-1.6°C	-2.4°C	-2.9°C	-3.3°C	-3.5°C	-3.4°C	-3.4°C
September	3.7°C	0.2°C	-0.6°C	-1.0°C	-1.4°C	-2.1°C	-2.6°C	-3.0°C	-3.3°C	-3.3°C	-3.3°C
October	-1.8°C	-0.1°C	-0.5°C	-0.9°C	-1.2°C	-1.8°C	-2.3°C	-2.7°C	-3.1°C	-3.2°C	-3.3°C
November	-5.3°C	-0.4°C	-0.5°C	-0.8°C	-1.1°C	-1.7°C	-2.1°C	-2.5°C	-2.9°C	-3.1°C	-3.2°C
December	-7.2°C	-3.1°C	-2.0°C	-1.7°C	-1.5°C	-1.7°C	-2.0°C	-2.3°C	-2.7°C	-2.9°C	-3.1°C
2015											
January	-12.6°C	-9.0°C	-7.1°C	-5.7°C	-4.6°C	-3.2°C	-2.6°C	-2.5°C	-2.6°C	-2.8°C	-3.0°C
February	-14.7°C	-12.3°C	-10.5°C	-8.9°C	-7.5°C	-5.3°C	-3.9°C	-3.2°C	-2.9°C	-2.8°C	-2.9°C
March	-11.5°C	-10.5°C	-9.8°C	-9.0°C	-8.3°C	-6.7°C	-5.3°C	-4.2°C	-3.3°C	-3.0°C	-3.0°C
April	0.0°C	-4.4°C	-5.9°C	-6.7°C	-7.0°C	-6.7°C	-5.8°C	-4.9°C	-3.9°C	-3.3°C	-3.1°C
May	8.7°C	-1.3°C	-2.7°C	-3.7°C	-4.3°C	-5.2°C	-5.2°C	-5.0°C	-4.3°C	-3.6°C	-3.3°C
June	12.2°C	-0.5°C	-1.6°C	-2.4°C	-3.0°C	-4.0°C	-4.4°C	-4.5°C	-4.2°C	-3.8°C	-3.5°C
July	13.1°C	0.0°C	-1.1°C	-1.7°C	-2.2°C	-3.1°C	-3.7°C	-4.0°C	-4.0°C	-3.8°C	-3.6°C
August	9.0°C	0.4°C	-0.8°C	-1.3°C	-1.7°C	-2.6°C	-3.1°C	-3.6°C	-3.7°C	-3.7°C	-3.6°C
September	3.8°C	0.2°C	-0.6°C	-1.0°C	-1.4°C	-2.2°C	-2.7°C	-3.2°C	-3.5°C	-3.5°C	-3.5°C
October	-0.5°C	-0.1°C	-0.5°C	-0.9°C	-1.3°C	-2.0°C	-2.5°C	-3.0°C	-3.3°C	-3.4°C	-3.4°C

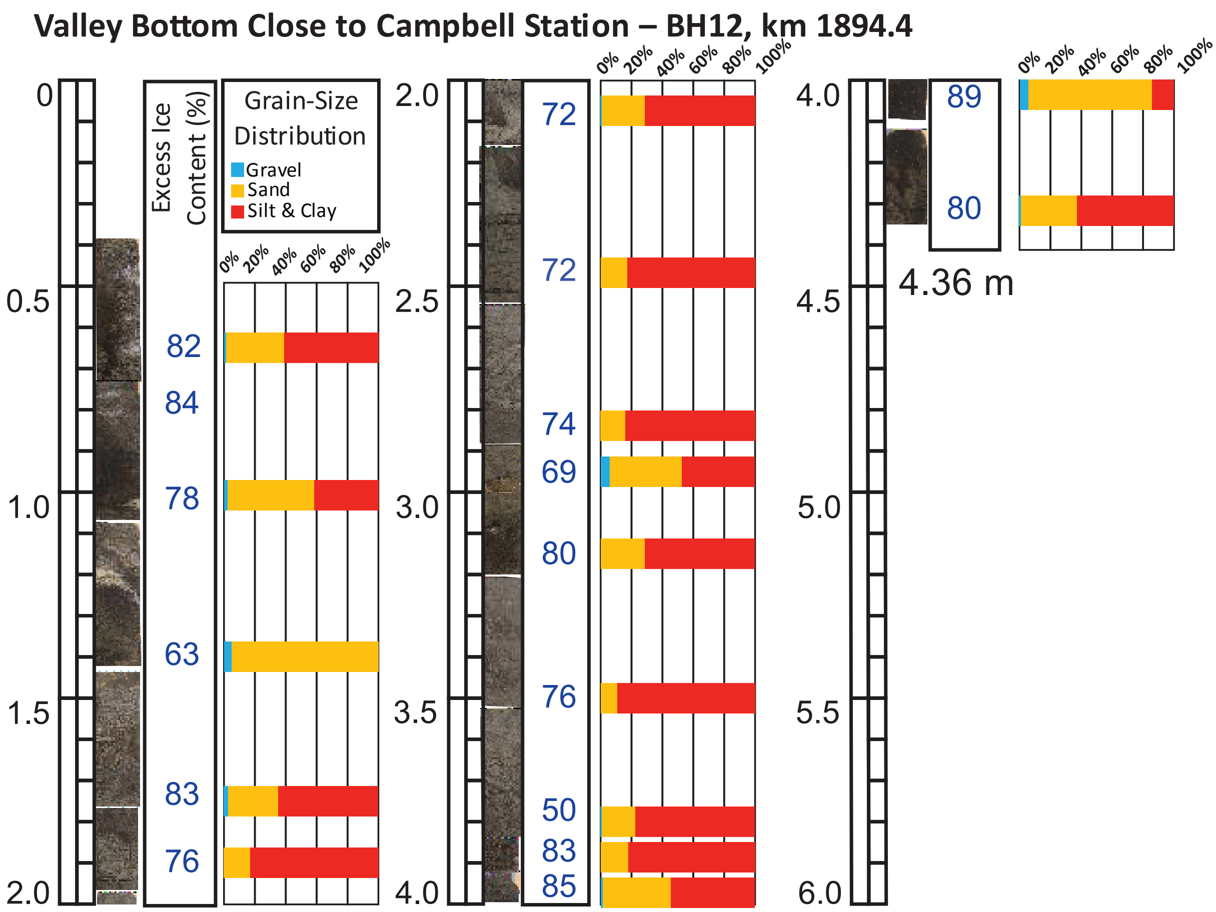


Figure 4.6.2. Log of BH12 borehole.

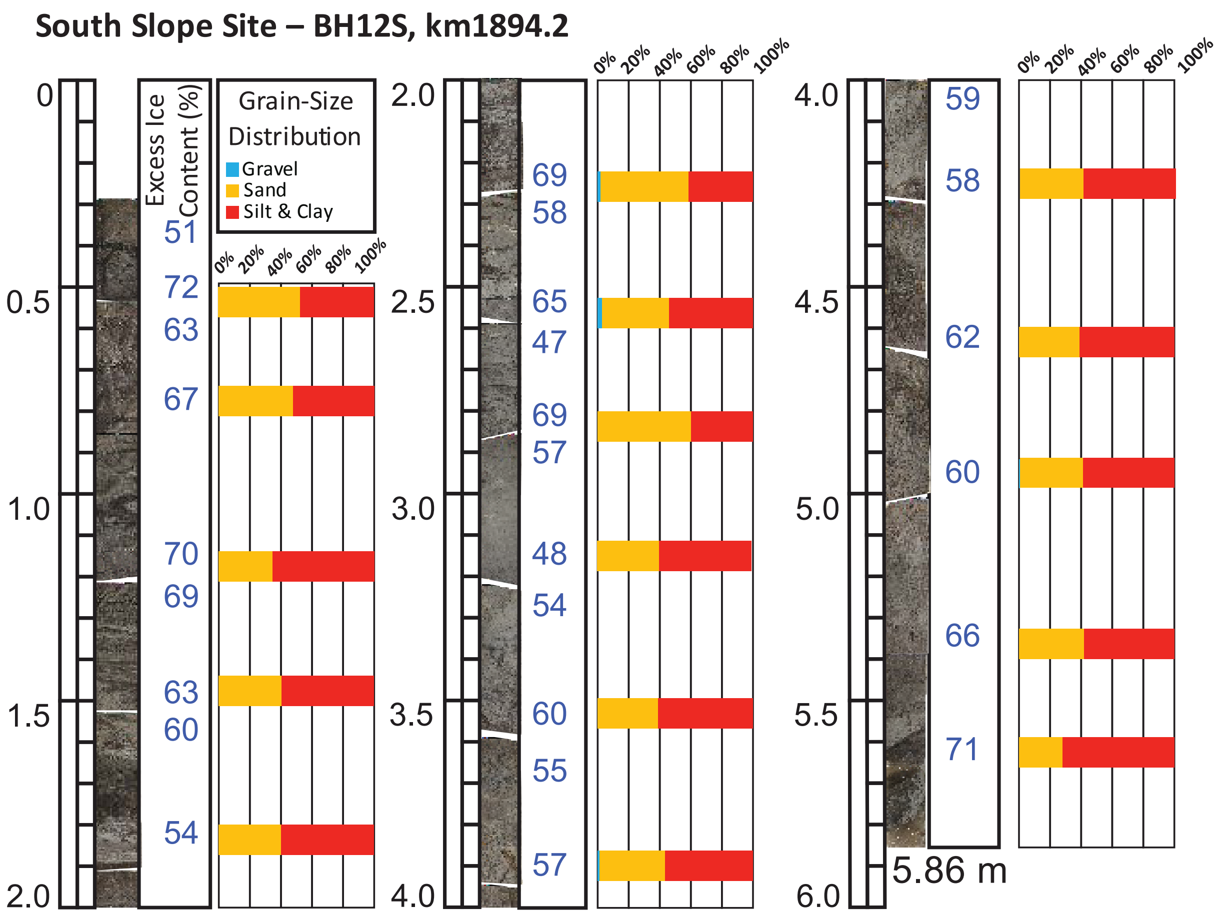


Figure 4.6.3. Log of borehole BH12S.

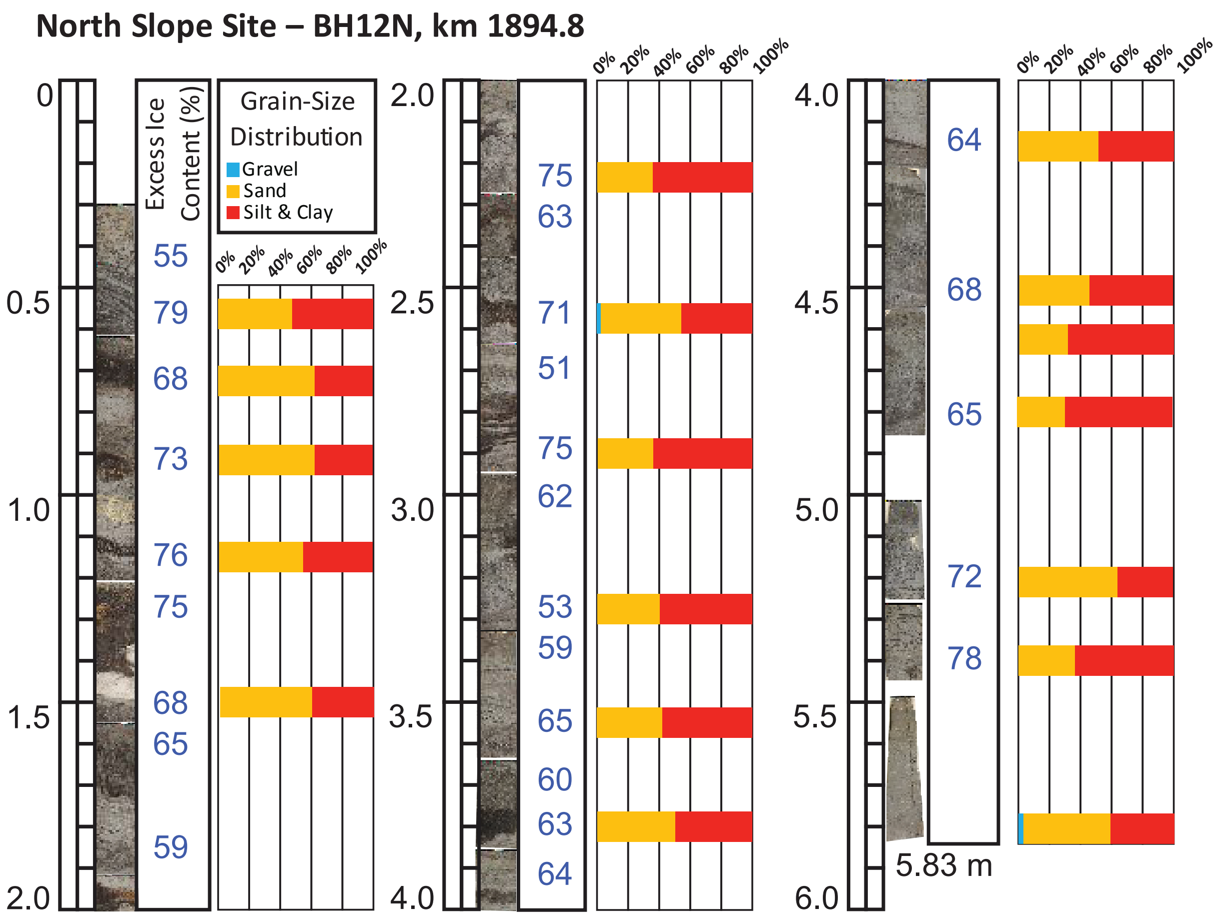


Figure 4.6.4. Log of borehole BH12N.

SUBSURFACE EXPLORATION AND TEST REPORT	**Alaska Highway - Site 5 - BH12 area**	SOURCE/TP#: **866-5308**
Boart Longyear	Establishment of Baseline Data, km 1894.5 LHS	PROJECT NO: 552-202021-0601-05-1
Sonic Drill	Coordinates: Z Nm Em	ELEVATION: m

SAMPLE TYPE: UNDISTURBED, DCPT, AUGER, BULK, SPT, CORE

SOIL DESCRIPTION	Depth (m)	SOIL DESCRIPTION	Depth (m)
ORGANICS -Dark brown, woody/fiberous		-Nbe	
ORGANIC SILT with ICE -Dark brown, frozen -Vx-Nbe, 40%	1	-SILT -Dark grey, Nbe -Clay lenses	11
-Some woody organic inclusions -Vx ~7%	2		12
-Vx ~25%	3	-Organic inclusions -Vx	13
PEAT -Woody, black			
ICE and PEAT -Vs, 8-10mm ice, 20-40mm peat	4	-Dark grey, Nbn -No clay	14
ICE and ORGANIC SILT -Vs, 10mm dark brown, cloudy ice -30mm Dark brown silt -Some organic inclusions, woody and fiberous	5		15
ICE and SILTY SAND -Vr, clear, white ice. Vs ends -Some fiberous inclusions	6		16
	7	-Some clay	17
ORGANIC SILT with ICE -Dark grey -Vx, ~20-40%, Clear, white	8		18
-Nbe	9		19
		END of HOLE	

Yukon Highways and Public Works, Transportation Engineering Branch	LOGGED BY: R.Stilwell	Termination Depth: 19.8m
	COMPILED BY: R.Stilwell	Complete: 9/11/2015 7:00:00 PM
	REVIEWED BY:	

Figure 4.6.5. Log of borehole HPW 866-5308.

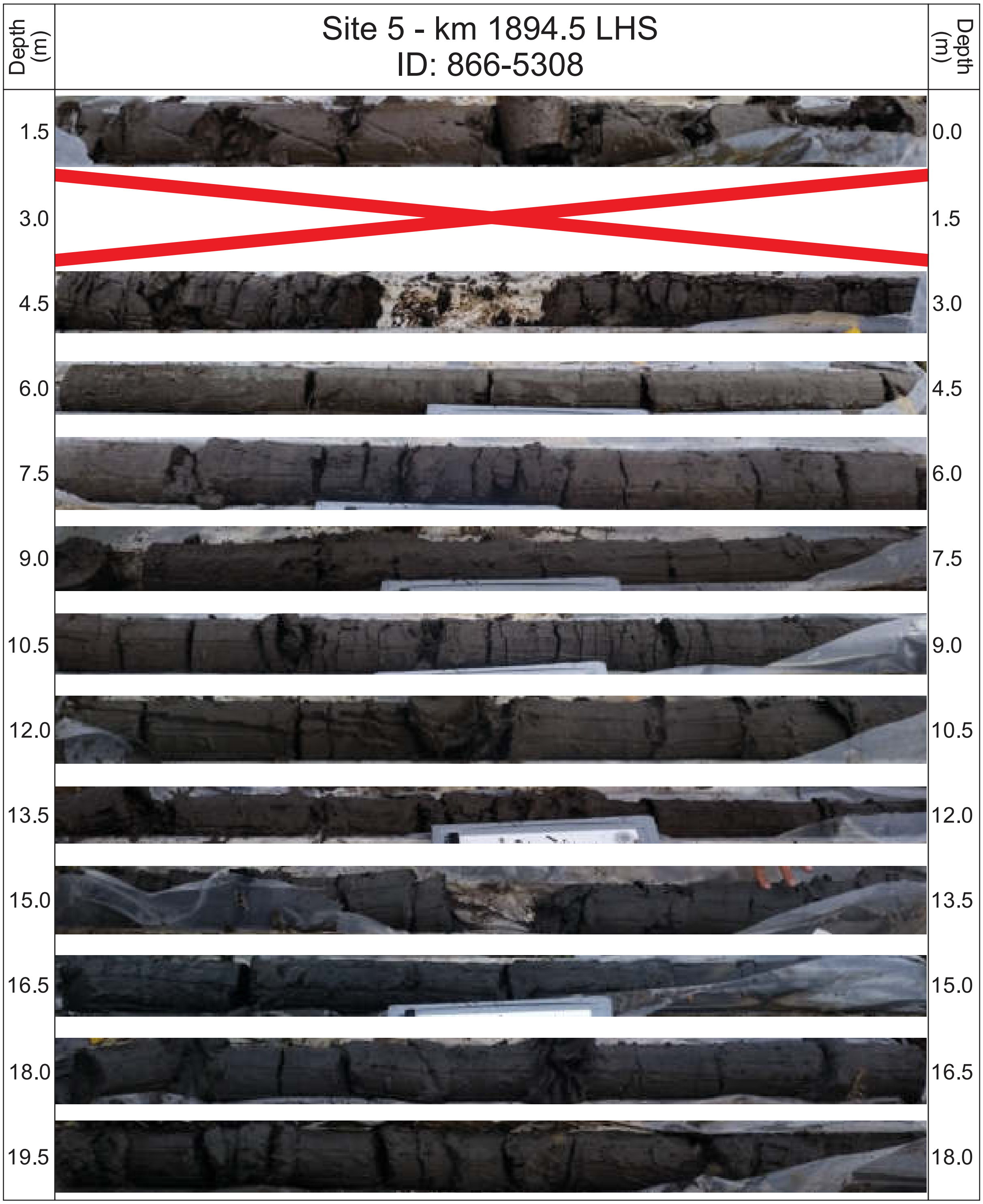
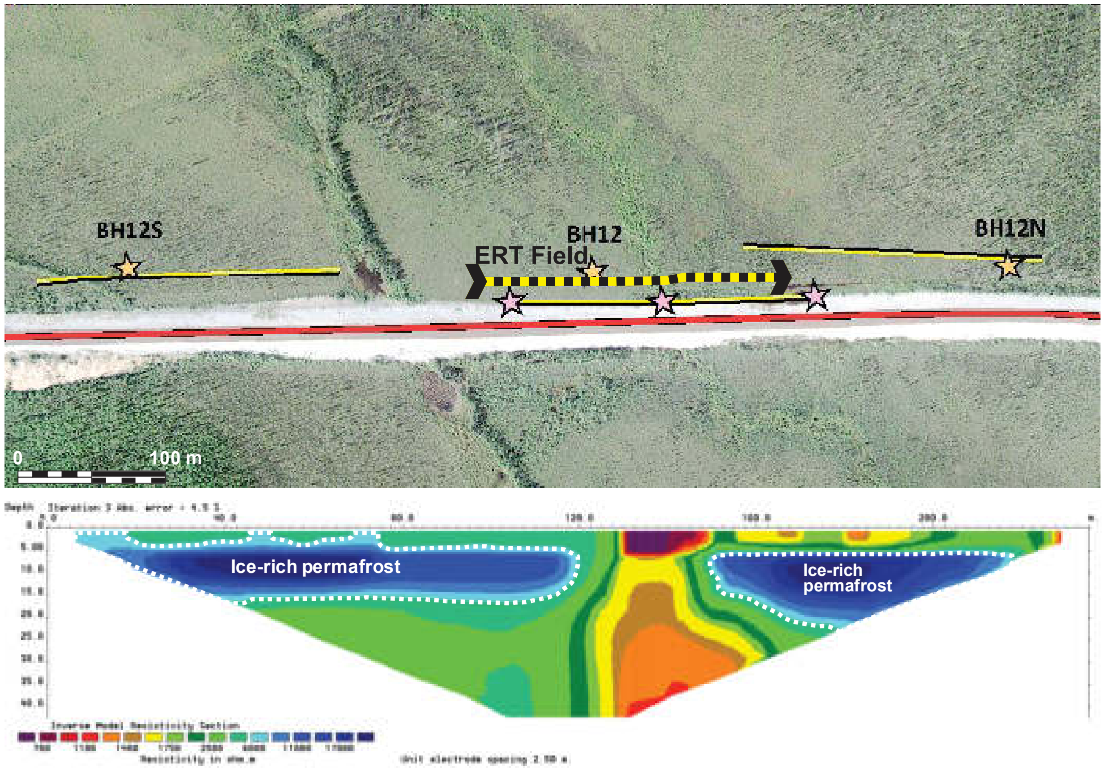
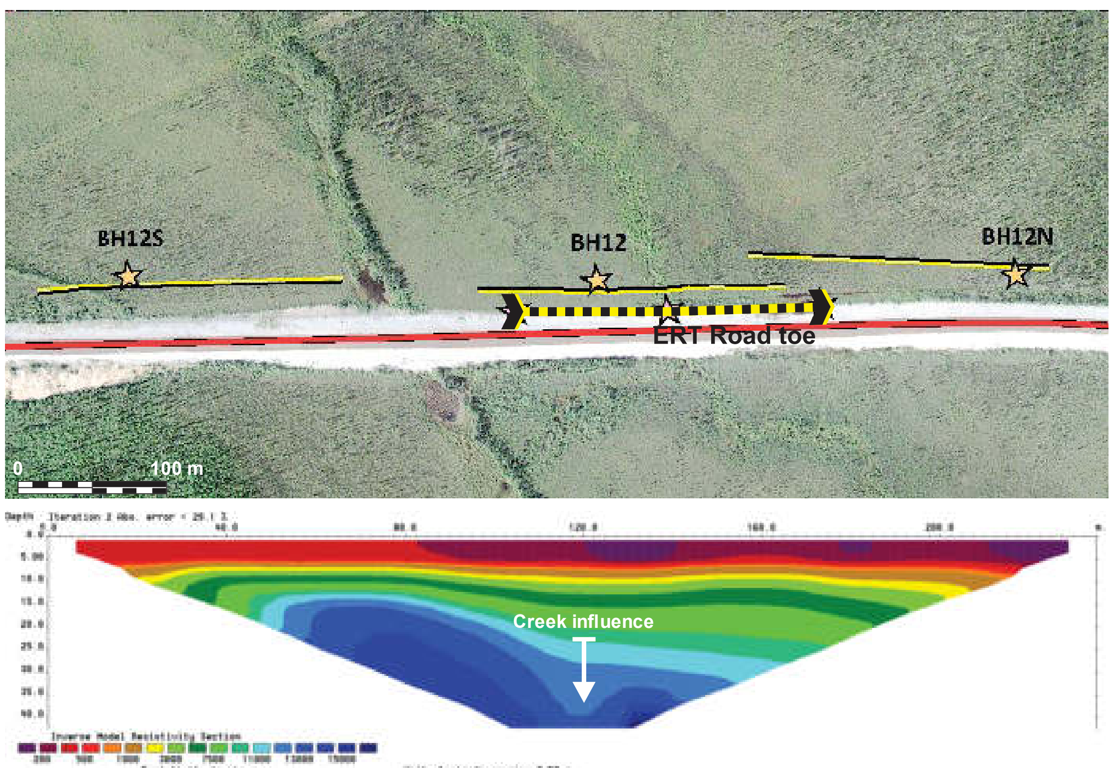


Figure 4.6.6. Cores collected from borehole HPW 866-5308.



A)



B)

Figure 4.6.7. ERT Surveys performed at borehole BH12 for A) the field; and B) the toe of the highway embankment.

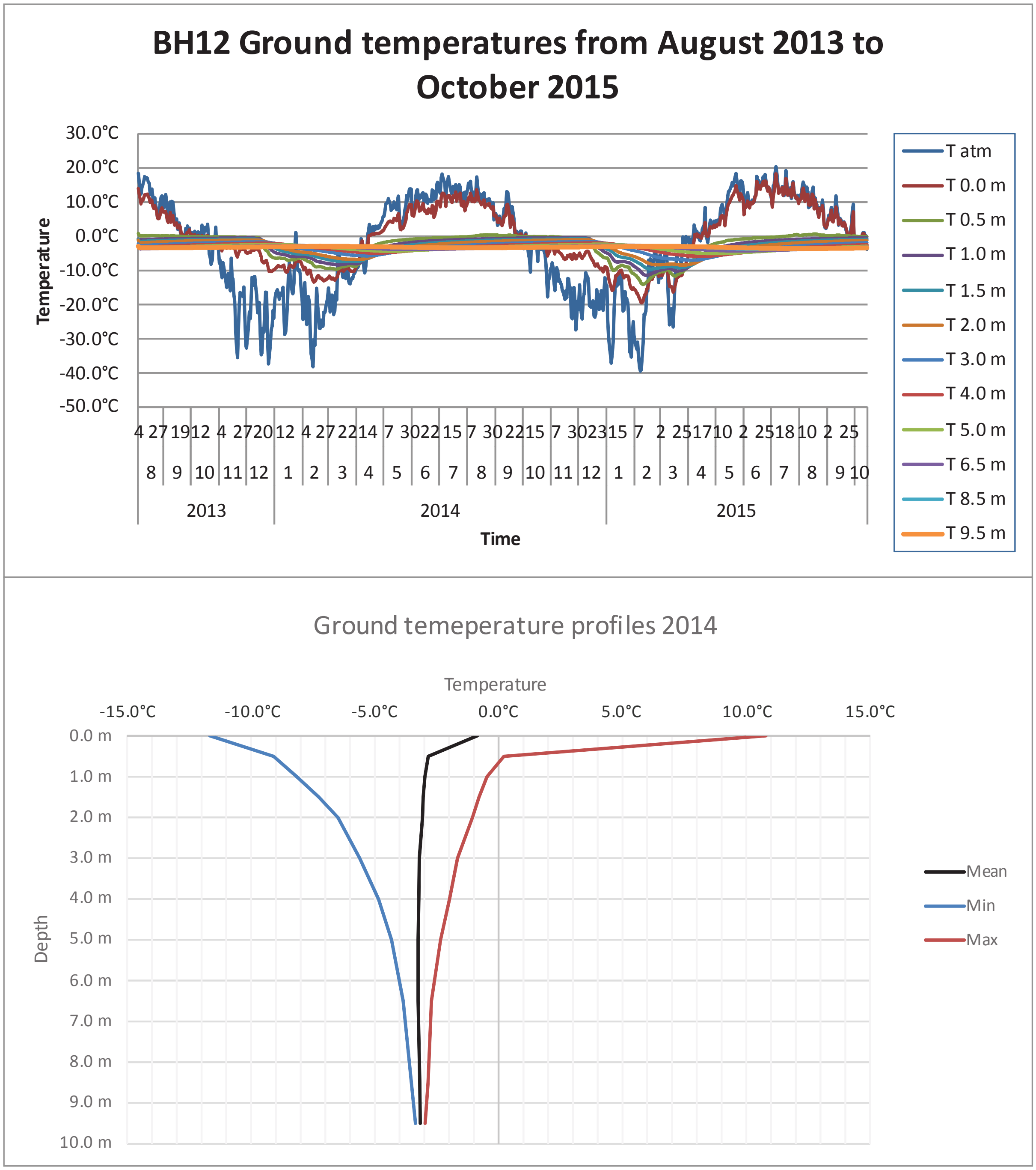


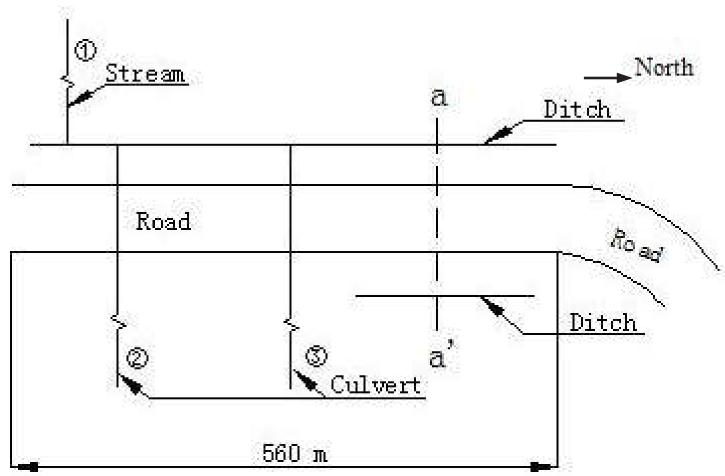
Figure 4.6.8. Ground temperature recorded in borehole BH12 from August 2013 to October 2015.

4.6.2 Adaptation design

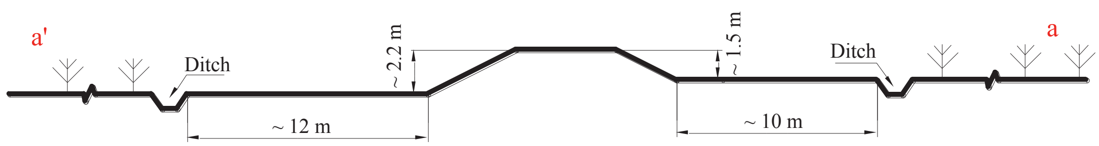
This proposed adaptation site is located at km 1894.8 in a valley surrounded by hills. The surficial geology consists of fluvial deposits comprised of silts, clay and sand. As shown in Figure, when facing north, the embankment height is approximately 1.5 m on the right hand side (east) and 2.2 m on the left hand side (west). Figure 4.6.9 shows different views of both right and left hand sides of the studied section of the road.

The vegetation consists mainly of trees, shrubs, grass, and moss. The forested area varies in density some areas being denser than others, notably closer to the hills. Following the reconstruction of the site in 2013, black, organic rich soil was spread along the toe of the embankment. Since then, vegetation, mostly consisting of grasses has started to develop at the toe of the road.

Some notable features of this site are two ditches that were dug in 2013, parallel to the road. The distance between the toe of the embankment and the ditches, are about 12 m at the left hand side, and 10 m at the right hand side. They are 4 m wide and 1.5 m deep, the shortest one being at the right hand side (Figure 4.6.9). A camera has been fixed near the long ditch to monitor the development of the ditch slump. The result shows that this ditch is strongly affected by thermal erosion and is becoming wider (Figure 4.6.10). A stream (① in Figure 4.6.9A) is intercepted by the ditch at the left hand side, flowing perpendicular to the ditch. Yet the ditch cut an ice wedge, at the same level as the stream that is also perpendicular to the ditch and the embankment. From spring to fall, the stream is fed by runoff water, and erodes the ice wedge. Now, thermal erosion has developed and is incising the terrain starting from the ditch to the west, exposing additional ice-rich permafrost and wedge ice. Besides stream (①), water also was flowing through culverts (② and ③ in Figure 4.6.9A) at the time of site visit in October 2015.



A)



B)

Figure 4.6.9. Schematic illustration of the North of Beaver Creek adaptation site for A) Localisation of proposed embankment cross section in transverse profile; and B) a-a' embankment cross section, km 1894.8

A)

B)

Figure 4.6.10. North of Beaver Creek adaptation site, km 1895 for A) Right and left sides of the embankment, facing south; and B) Left and right sides of the embankment, facing north

Figure 4.6.11. Thermal erosion in the ditch, facing southwest.

4.6.2.2 Site thaw sensitivity

The NCE boreholes located in the field at the left hand side shows that the excess ice content can be as high as 89%. This is attributable to the presence of ice-rich organic silt and wedge ice. An HPW borehole down to the depth of 19.8 m shows high excess ice content in the first 10 m of the profile.

ERT surveys suggest that permafrost can be ice-rich down to 20 m. This would be due to the presence of syngenetic ice wedge complexes. The recorded ground temperature oscillates between -3.0 and -3.6°C at the depth of 9.5 m.

If one consider the excess ice content, the thickness of permafrost (that could be as thick as 60 m), and the relatively cold ground temperature, one can expect that this thaw-sensitive permafrost will undergo a long-lasting degradation. The thermal erosion processes observed on the site also suggest that the magnitude of the ensuing settlements and damages will be major.

Air temperature and precipitation are expected to increase in the future. These will exacerbated and accelerate permafrost degradation. The thermal erosion that is already active at this site may lead to more settlements and slumping along the ditches. To summarize, while the permafrost is relatively cold at Site 6, its excess ice content and significant thickness make it highly thaw-sensitive.

The detailed information about Site 6 is summarized in Table 4.6.2.

Table 4.6.2. Detailed information of site 6

Permafrost distribution (ice-rich) (Underground)	MAGT (°C)	Height Difference (m)	
		Right Side	Left Side
3 m ~ more than 20 m	-3.3	1.5	2.2
Excess ice content (Maximum)	**Soil Types**	**Climate Warming(°C)**	
		2030s	**2050s**
89%	Mainly fine-grained	1.5 ~ 2.0	3.5 ~ 4.0
Vegetation (Land Cover)	**Surficial Material**	**Drainage Condition**	
About 70%	Fluvial	Ditches along each side	

4.6.2.3 Adaptation suitability

Many of the criteria required to apply mitigation techniques, described at the beginning of Section 3, are found at Site 6. Permafrost is relatively cold, below -3°C; due to the presence of ice wedge complexes along the profile, the excess ice content exceeds 40%; finally the base of permafrost was not directly observed, but is expected to be as deep as 60 m. Also, the section is straight, without notable curves or slopes.

Nevertheless, an important selection criterion is to avoid area affected by obvious convective water flow, which can reduce the effectiveness of proposed mitigation techniques. At site 6, water erosion is active, causing substantial subsidence in the field. As a result, this site is not selected to be adapted to climate change with permafrost mitigation techniques. Yet, it is recommended to continue to strictly monitor the site, as further thermal erosion may propagate below the embankment and cause caving and other substantial damage.

5. SUMMARY & CONCLUSION

In the context of the present survey, six candidate sites were assessed for their suitability to implement adaptation measures along the Northern 200 km Yukon section of the Alaska Highway. The adaptation measures aim to preserve permafrost thermal equilibrium under a warming climate. Following field assessment that involved geotechnical and geomorphological assessment, as well as permafrost characterization, four sites were retained for preliminary design of adaptation measures. The length of the sections considered for remediation varies from 350 m to 1000 m. Each section is located on highly thaw-sensitive permafrost and has a high vulnerability to climate change. Two sections were rejected because of the occurrence of major water bodies and streams nearby the site, or because permafrost degradation is already advanced enough that remediation techniques may not be able to restore thermal equilibrium.

For each road section, a total of six adaptation techniques were considered in the preliminary adaptation designs. The implementation of ACE, HD, HAS, insulation, thermosyphons, and snow and sun sheds was considered for the preliminary designs presented in section 3 of this report. Table 5.1 present a summary of proposed adaptation techniques for each section.

Table 5.1. Proposed remediation techniques for the four sites considered suitable for adaptation.

Site	Cross-section* a – a' (km)	Mitigated section (km)	Lenght (m)	Design
Koidern No.2	1809.5	1808.6-1809.6	1000	• ACE U shape • ACE on shoulder + HAS • HD + HAS
Dry Creek	1840.6	1840.55-1840.9	350	• ACE U shape • Thermosyphons • HD + HAS
Enger Creek	1863.5	1863.3-1864.3	1000	• HAS with sun/snow shed • HAS + insulation in shoulders • HAS alone
Mirror Creek	1886.1	1886-1887	1000	Rejected
US Border 1	1894.8	1894.4-1894.9	500	Rejected
US Border 2	1896.3	1986-1896.8	800	• ACE on shoulder + HAS • Insulation in shoulder + HAS • HD in shoulder + HAS

* Refer to site and design drawings.

** Including an 80 m section with recommended thermosiphon design.

Ideally, a 1000 m section should be adapted at each site to provide an adequate length to fully assess the performance of the adaptation and to understand costs and benefits of the design. However, not all sites will allow this length due to the presence of curves (Dry Creek km 1840, US Border km 1896). While the design is provided for the total length of each section, additional, more localized techniques can be considered for a short lengths within some sections. For example, thermosyphons are only suggested for a length of 50 m at the thermokarst area of the Dry Creek site.

In all, twelve designs options are suggested (three options per site). Four of the proposed design options rely on the application of one technique, while eight design options involve the use of two or more techniques in combination. High albedo surface is suggested at all four sites and is included as part of nine suggested design options. The use of ACE ranks second, included in four design options at three sites. HD are part of three design options, suggested at 3 sites. Insulation is suggested in two design options and at two sites. Thermosyphons are used in one design for Dry Creek, and sheds are suggested for one design at Enger Creek.

It has to be noted that the proposed remediation approaches only apply to the road itself (i.e. the embankment). Additional adaptation measures might be advised for the surroundings of the remediated sections. For example, at Dry Creek, reclamation of excavated areas using organic soil and revegetation may help to improve permafrost preservation at the vicinity of the road.

Finally, while this report focusses on the reconstruction and adaptation of highway sections threatened by permafrost degradation, all of these designs should be accompanied by a carefully considered monitoring programin order to closely measure the performance of the adapted site.

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