Alaska University Transportation Center PROJECT
Use of Geophysical Methods in Subsurface Investigations for Arctic/Subarctic
Transportation Planning and Maintaining
Application #1: Highway Planning in Discontinuous Undisturbed Permafrost

Report of Activities
Geophysical investigation along the realignment of Dalton Highway
at 9-Mile Hill near Livengood
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May 20th 2010
Cover photograph

Electrical resistivity tomography in progress along the survey line at 9-Mile Hill study site, Dalton Highway.
Introduction

This report of activities presents the preliminary results of a geophysical investigation undertaken along the realignment of Dalton Highway at 9-Mile Hill near Livengood. The principal goal of this investigation is to assess the spatial distribution of permafrost conditions along the realignment based on the interpretation of geophysical surveys including the information from boreholes.

The Alaska Department of Transportation and Public Facilities (ADOT&PF) is investigating the reconstruction of approximately 4 miles of the Dalton Highway between the mile post (MP) 8 and 12 (Figure 1) to current design standards for providing safer alignments, grades, and a new asphalt surface. The project area is located about 10 miles east of Livengood and 80 miles north of Fairbanks. The Trans-Alaska Pipeline parallels the Dalton Highway and is located approximately 1.5 miles to the east of the project location. The three mile long realignment is sloping gently to the north-west. According to Péwé (1975) and Jorgenson et al. (2008), the study area is in the discontinuous permafrost zone. The bedrock is made of highly deformed and weathered sedimentary rocks, and overlain by colluvial and fluvial gravelly soils, and silt (loess). Permafrost formed syngenetically during the late Pleistocene is ice-rich with high occurrence of ice wedges.

Over the last 20 years, the Northern Region Materials Section (NRMS) conducted four separate geotechnical investigation of the project area including several boreholes (Schlichting et al., 2006). In 2008, 8 boreholes were drilled for permafrost sampling to allow the detailed description of cryostructure (Shur and Kanevskiy, 2010). The ground-truth coming from these boreholes offers a unique opportunity to verify the capabilities of geophysical methods for permafrost investigation along linear man-made infrastructures with well-documented borehole data.
Reconnaissance missions and geophysical investigation program

Before carrying out the geophysical investigation along the realignment of Dalton Highway at 9-Mile Hill near Livengood, the study site was visited twice for reconnaissance purpose.

During the first mission on April 20\textsuperscript{th} 2010, Richard Fortier and Mikhail Kanevskiy put markers at regular 25-m interval along the survey line (Figure 2). The borehole UAF-4 was selected as the reference position at 0+000 m. The distance along the survey line increases going north. The snow cover about 1-foot thick was rapidly
decaying at that time (Figure 3). It was decided to postpone the geophysical investigation in the coming weeks after the snow melting.

Figure 2: Projected realignment of the Dalton Highway between the MP 8 and 12.
The second mission took place two weeks later on May 5\textsuperscript{th} 2010. Richard Fortier and Mikhail Kanevskiy walked the survey line and measured the ground temperatures along thermistor cables in the boreholes 08-040, 08-046 and 08-053 (Figures 4 and 5). The ground temperature at a depth of 10 m is -1.5, -0.5 and -1.7 °C in the boreholes 08-040, 08-046 and 08-053 respectively. The permafrost temperature is colder in the bottom hill near the Dalton Highway and at the top of the hill than at the middle hill. They measured also the contact resistance between two electrodes driven 2-m apart at several locations along the survey line in the active layer using an ohmmeter. In average, the resistance contact was 10.1 kohm. The thawing front was only few centimeters deep and most of the active layer was still frozen on May 5\textsuperscript{th} 2010. Even if this contact resistance was judged a little bite too high for the measurement of electrical resistivity using galvanic contacts, it was decided that the geophysical surveys would be carried out in the coming days.
Figure 4: Thermistor cable in borehole 08-053 (see Figure 2 for its location). Note the absence of snow cover on May 5th 2010.

Figure 5: Ground temperatures measured along the thermistor cables in boreholes 08-040, 08-046 and 08-053 (see Figure 2 for their location) on August 11th 1998 and May 5th 2010.
The geophysical investigation along the realignment of Dalton Highway at 9-Mile Hill near Livengood was performed from May 7th to May 10th and on May 20th 2010. Electrical resistivity tomography (ERT) and ground penetrating radar (GPR) profiling were carried out in the field. Two types of ERT were conducted: 1) direct-current resistivity (the standard method), and 2) capacitive-coupled resistivity (CCR) measurements. These geophysical tools used along the same survey line are complementary methods (De Pascale et al., 2008; Fortier and Bolduc, 2008; Fortier and Savard, submitted). While ERT is effective for characterizing the state of the permafrost, it does not define well the subsurface stratigraphic contacts. GPR, on the other hand, defines accurately the stratigraphy contacts, but does not provide as much information with respect to the state of the permafrost. The combined interpretation of the ERT and GPR can therefore lead to a high resolution cross-section of permafrost conditions. They were successively used to map massive ice, ice wedges, thermokarst, and basic stratigraphic relationships (De Pascale et al., 2008) and permafrost conditions underneath a road embankment (Fortier and Bolduc, 2008) and an airfield (Fortier and Savard, submitted). The galvanic contact ERT was carried out by Richard Fortier and William Lee from May 7th to May 9th while the CCR-ERT was conducted by Kevin Bjella from the CRREL, Richard Fortier and William Schnabel. Richard Fortier and Erin Trochim were in charge of the GPR profiling.

Among the available near-surface geophysical methods, electrical resistivity tomography (ERT) is a powerful tool for permafrost investigation because the electrical resistivity of a medium is highly sensitive to the transition from unfrozen to frozen state.

Values of apparent electrical resistivity for the galvanic contact ERT were measured using an Earth Resistivity/IP Meter SUPER STING R1 IP (Figure 6) from AGI Advanced Geosciences Inc. (http://www.agiusa.com). This earth resistivity meter is made of 4 cables of 21 connectors 2-m apart each for a total of 84 electrodes driven into the ground for galvanic contacts. A Wenner array with 2-m spacing between the electrodes was used to perform the ERT with a theoretical depth of investigation from 1 to about 25 m. The electrodes were aligned along the survey line. The electrodes selection for direct injection of electrical current into the ground and measurement of induced electrical potential was made automatically by the earth resistivity meter according to a previous array programming downloaded in the SUPER STING R1 IP. Once the 84 electrodes were scanned by the earth resistivity meter, one cable of 21 connectors at the beginning of the ERT was moved at the other end to perform a “roll along” and increase the ERT length. In total, 11 “roll alongs” were performed for a total ERT length of 640 m. The location of the ERT ends is given in Figure 7. The galvanic contact ERT was carried out from north to south.

The data set of apparent electrical resistivity measured with the SUPER STING R1 IP is presented in Figure 8 under the form of a pseudo-section of measured apparent electrical resistivity. This data set was also inverted using a quasi-Newton method (Loke and Barker 1996) and the software packages RES2DINV (Loke 1996) to produce a model of electrical resistivity (Figure 8). This preliminary model does not take into account the topography effect along the survey line. The root–mean–square error
(RMS error) between the calculated and measured values of apparent electrical resistivity is 10.6% after 3 iterations. The downhill section of the ERT survey is more resistive than the uphill section (Figure 8). The contrast in electrical resistivity between these two sections is located at a distance 0+630 m along the survey line. The ERT survey covers in part the sections 1 and 2 (Figures 1 and 7) as identified by Shur and Kanevskiy (2010). The permafrost in section 1 is ice-rich with a high occurrence of ice wedges while the one in section 2 is ice-poor. Based on the analysis of boreholes, Shur and Kanevskiy (2010) located the limit between these two sections at a distance of 0+300 m relative the reference location at UAF-4 (Figures 1, 2, and 7).

Figure 6: Earth Resistivity/IP Meter SUPER STING R1 IP (Figure 6) from AGI Advanced Geosciences Inc. Electrical resistivity tomography performed along the survey line at 9-Mile Hill study site, Dalton Highway.
Figure 7: Location of the geophysical surveys carried out along the realignment of Dalton Highway at 9-Mile Hill near Livengood.

Figure 8: Results of galvanic contact ERT (see Figure 7 for location). Pseudo-sections of measured and calculated apparent electrical resistivity, and model of electrical resistivity along the realignment of Dalton Highway at 9-Mile Hill near Livengood. The north direction is on the left.
The CCR system is made of one transmitter and one up to five receivers to achieve a dipole-dipole configuration (Figure 9). The transmitter and receivers are coaxial cables lying on the ground as antennas to couple an AC signal into the ground and measure the induced AC signal respectively. The conductor in the coaxial cable acts as one plate of a capacitor and the ground acts as the other plate while the insulating sheath of the coaxial cable is the capacitor's insulator. The AC current in the transmitter cable can pass into the ground similarly to an AC signal through a capacitor. The capacitance of the receiver cable is similarly charged, allowing the measurement of an induced AC voltage in the receiver proportional to the electrical resistivity of the ground. This provides an AC equivalent of a standard DC resistivity measurement without the galvanic contacts needed for the standard method (for more details on the theory behind CCR, see Timofeev et al. 1994 and Kuras et al 2006). This is a major advantage since it can be hard to drive electrodes in frozen active layer or man-made infrastructures such as a pad of highly compacted crushed rocks of an embankment. Moreover, since the system does not depend on surface contact, it can be towed on the ground surface while collecting data for fast investigation along a linear infrastructure such as road or planned realignment of a road. According to Kuras et al. (2006), the DC resistivity measurement is emulated through CCR when the ground resistivity is high such as the dry surface of an embankment. The CCR is therefore a geophysical tool well suited to permafrost investigation.

The apparent electrical resistivities along the realignment of Dalton Highway at 9-Mile Hill near Livengood were also measured using an OhmMapper TR5 system with one transmitter and five receivers operating at a frequency of about 16.5 kHz made by GEometrics. The OhmMapper is owned by the Cold Regions and Research Engineering Laboratory (CRREL). The location of the ends of the CCR-ERT survey line is given in Figure 7. The CCR-ERT survey line is longer than the one of the galvanic contact ERT since the production rate in terms of meter per day is much higher for the CCR-ERT than the galvanic contact ERT. Only one day was needed to achieve a longer ERT survey line with the CCR system in comparison to three days for the shorter one with the earth resistivity meter. Markers at regular 25-m intervals put along the survey lines allowed the location of the resistivity measurements relative to the reference position at borehole UAF-4 (Figures 2 and 7). Four runs with different dipole length and spacing between the dipoles were performed along the survey line (Table 1). The variation in spacing between the dipoles changes the depth of investigation for producing pseudo-sections of observed apparent electrical resistivity along the survey lines. The apparent electrical resistivities measured along the survey line for the four runs are given in Figure 10. The data have been despiked. The pseudo-sections of measured apparent electrical resistivity appear in Figure 11. The north end is more resistive than the south end. These preliminary pseudo-sections do not take into account the topography effect along the survey line. The merge of the data files of the four runs and the inversion of measured apparent electrical resistivity are not completed yet.
Figure 9: Capacitive-coupled resistivity (CCR) system: the OhmMapper TR5 made by Geometrics and owned by the CRREL.

Table 1: Electrode cable and dipole lengths, spacing and n factor between the dipoles, and theoretical depth of investigation for each run of the CCR-ERT survey.

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<th>Run</th>
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<th>Dipole length (m)</th>
<th>Spacing between the transmitter dipole and the 5 receiver dipoles (receiver number) (m)</th>
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Figure 10: Results of OhmMapper survey (see Figure 7 for location). Variations in measured apparent electrical resistivity along the realignment of Dalton Highway at 9-Mile Hill near Livengood (the receivers #1 to #5 are the red, blue, green, purple and yellow curves respectively). A to D) Run #1 to #4 (see Table 1). The north direction is on the right.
Figure 11: Results of OhmMapper survey (see Figure 7 for location). Pseudo-sections of measured apparent electrical resistivity along the realignment of Dalton Highway at 9-Mile Hill near Livengood. A to D) Run #1 to #4 (see Table 1). The north direction is on the right.
The ground penetrating radar (GPR) is used for a wide range of subsurface mapping applications to characterize the structure and stratigraphy of near-surface geology. This geophysical tool is made of a pair of transmitting-receiving antennas lying on the ground surface (Figure 12). At each position of the antennas along a survey line, few short electromagnetic impulses at a given nominal frequency are transmitted from the transmitting antenna in the ground and recorded and stacked for amplification by the receiving antenna over a given time period. The radar signal amplitude of each recorded trace is then plotted, one trace against the other, on a travel time profile (Figure 13). High amplitude on the profile corresponds to a reflection of the radar signal back to the surface on ground interfaces such as the water table and thawing front characterized by a contrast of dielectric permittivity.

A Sensors & Software pulseEKKO Pro with antennas of 100 MHz was used in the present geophysical investigation to perform two survey types: 1) fixed-offset reflection profile for stratigraphic mapping and 2) common mid-point (CMP) sounding for assessing the velocity of the radar signal in the ground. The GPR profile along the survey line is given in Figure 13 without and with the correction of the topography while one of the two GPR-CMP soundings performed along the survey line near the borehole UAF-9 at 0+960 m and its analysis are given in Figure 14. The analysis of a CMP sounding consists in stacking the data traces corrected in time for many different velocities to produce a travel time–velocity graph. When the corrected traces are stacked at an incorrect velocity, they tend to interfere destructively and to produce low amplitudes on the graph. When they are stacked at a correct velocity, they add together constructively and produce high amplitudes. The highest amplitudes on the travel-time-velocity graph are then associated with a velocity value. For instance, according to the analysis of the GPR-CMP sounding carried out along the survey line (Figure 14), the velocity of the radar signal varies between 0.09 and 0.13 m/ns for maximum value of about 0.1 m/ns. This value was used to transform the GPR travel time profile into a depth profile for assessing the depth of the reflectors (Figure 13).
Figure 12: Ground penetrating radar (GPR) pulseEKKO Pro with antennas of 100 MHz made by Sensors & Software inc.
Figure 13: GPR reflection profile (see Figure 7 for location) along the realignment of Dalton Highway at 9-Mile Hill near Livengood. A) Without and B) with the correction of the topography. The north direction is on the right.
Figure 14: A) GPR-CMP sounding (see Figure 7 for location) along the realignment of Dalton Highway at 9-Mile Hill near Livengood. B) Analysis of the GPR-CMP sounding is given on the right.
Processing and interpretation of geophysical surveys

The preliminary results of the geophysical investigation undertaken along the realignment of Dalton Highway at 9-Mile Hill near Livengood are given herein in this report of activities. The following steps remain to complete this geophysical investigation:

1) merge the data files of the four runs of the OhmMapper along the survey line,
2) produce the pseudo-sections of apparent electrical resistivity measured during the galvanic contact ERT and the CCR-ERT taking into the topography effect,
3) take into account the topography effect in the inversion of the pseudo-section of apparent electrical resistivity measured during the galvanic contact ERT and the CCR-ERT,
4) produce models of electrical resistivity from the inversion of the pseudo-section of apparent electrical resistivity measured during the galvanic contact ERT and the CCR-ERT,
5) compare the two models of electrical resistivity,
6) identify the permafrost conditions in the models of electrical resistivity,
7) correct the topography effect in the GPR reflection profile,
8) identify the cryostratigraphic contacts in the GPR reflection profile,
9) produce a cross-section of permafrost conditions and cryostratigraphic contacts along the survey line by combining the interpretation of the ERT and GPR surveys,
10) include the ground-truth information coming from the boreholes in the previous steps,
11) identify the zones vulnerable to permafrost degradation along the survey line,
12) write a final report, and
13) submit a manuscript on the results to a scientific journal.
References


