Noninvasive 3D Imaging and Characterization of Permafrost Profiles Using iFROST MAPPER

RESEARCH PROBLEM AND BACKGROUND

Permafrost is a type of soil that remains below the freezing point of water (0 ^{o}C) for two or more years. Most permafrost is located in the Earth's Arctic and subarctic regions and is a major consideration for critical infrastructure construction. Roads, structures, and pipelines constructed in these regions largely depend on the engineering behavior of frozen or unfrozen soils. Site surveying and characterization of permafrost properties are prerequisite for the design, construction and maintenance of critical civil engineering infrastructure in such cold regions. However, the spatial mapping of subsurface compositions of discontinuous permafrost remains challenging due to the presence of multiple phases (solid, air, ice, water) and the possible phase changes between water and ice. In cold regions, current mean annual temperatures are still below 0 ^{o}C, but have been projected to follow an increasing trend due to global warming (Chapman and Walsh, 2007). The changes in temperature will initiate widespread permafrost degradation with resulting effects on the physical, chemical and microbial properties of soils (Walker et al., 2006; Wolken et al., 2011). An improved understanding of the spatial distribution and physical properties of both continuous and discontinuous permafrost will provide insights into the future evolution of the permafrost environment. This will significantly advance engineering design and natural resource management strategies in cold regions.

Field-scale inspections of soil commonly resort to visual observations on soil surfaces. This requires that surveyors walk along the entire extent of earthen structures such as embankments and slopes for soil structure observation and measurement (Kleppe and Olsom, 1985, Dasog and Shashidhara, 1993, Morris et al., 2007), destructive techniques such as the excavation of trenches (Cooling and Marsland, 1954, Dyer et al., 2009), and nondestructive geophysical surveys such as Electrical Resistivity Tomography (ERT) (Sentenac and Zielinski, 2009, Jones et al., 2012, Chambers et al., 2012, Jones et al., 2014, Gunn et al., 2015). However, visual surveying cannot clearly reveal subsurface soil structures , resulting in low accuracy predictions of soil performance (Jones et al., 2014). Although the actual subsurface soil profiles can be exposed through trenching or sampling, such invasive and destructive techniques are time-consuming, laborious, and more importantly, may disturb the original soil structure resulting in less reliable evaluations. Therefore, a non-destructive method such as ERT has emerged as a popular alternative, which overcome many of the aforementioned limitations yielding efficient, high fidelity soil profiles.

Measurement of the electrical resistivity of soil is a well known technique that can yield important information about many soil properties, including the nature of solids (mineralogy, shape, fabric, and size distribution), arrangement of voids (porosity, tortuosity, connectivity, pore structure), and properties of fluids (water content, electrical resistivity, solute concentration) (Archie, 1942, Keller and Frischknecht, 1966, Arulanandan and Muraleetharan, 1988, Thevanayagam, 1993, Andrews et al., 1995, Gibert et al., 2006, Chambers et al., 2012, Gunn et al., 2015). The interplay of these component factors determines the movement of anions and cations under the application of an applied electrical field, which results macroscopically as variation in soil resistivity. The heterogenous nature of soil may strongly influence resistivity measurements; for example, the presence of cracks in soil may result in substantially altered resistivity measurements compared to results from more homogenous soils (Samouëlian et al., 2004, Samouëlian et al., 2005).

The electrical resistivity/conductivity values of permafrost have been reported in several studies using either direct electrical methods or through electromagnetic induction (EMI) techniques. Partly- or fully-saturated silty sand or fluvial gravel typically yields electrical conductivity values of above 2 mS/m to below 2.9 mS/m in unfrozen and frozen states, respectively (Hoekstra et al. 1975; Minsley et al. 2012). The presence of clay can yield higher electrical conductivities: 100 mS/m when unfrozen and 20 mS/m when frozen (Minsley et al. 2012). Saline solutions within soil pores also strongly influences electrical conductivity and freeze point of soils. Much higher values of electrical conductivity may be found—e.g., up to 1000 mS/m (Overduin et al. 2012). The large variations make electrical resistivity/conductivity-based characterization challenging in highly saline coastal regions, but very suitable for areas with clear contrast between frozen and unfrozen layers.

As electrical resistivity is extremely sensitive to water content, many empirical relationships between resistivity and water content have been established. To deduce other soil properties such as shear wave velocity and overconsolidation ratio that are closely related to soil stiffness and strength, it is important to establish correlations between the spatial variation of electrical resistivity and geotechnical data such as soil physical properties, average N-values obtained from Standard Penetration Tests (SPT), Dynamic Cone Penetration Tests (DCPT), or Cone Penetration Tests (CPT). The correlation is expected to be sensitive to the degree of saturation, ice content, clay content, and lithology at the investigated sites.

DIRECT BENEFIT TO MILITARY ENGINEERING

1. This project will lead to the development of a novel permafrost assessment and mapping system (PAMS) consisting of measurement devices and methods for rapid and noninvasive permafrost soil characterization in cold regions. The system will be capable of acquiring and analyzing resistivity survey data, deduce soil physical and mechanical properties, and map associated 3D geographical and geotechnical profiles.
2. The advances achieved with PAMS will shorten the time needed for site investigation and thereby speed construction of vital infrastructure in cold regions.

RESEARCH GOAL AND OBJECTIVES

The overall goal of this study is to perform the background research, development and testing needed to achieve a noninvasive, three-dimensional, and rapid imaging and characterization system (PAMS) that provides permafrost soil profiles and assessment of soil properties. Initial evaluations will be based on Time Domain Electromagnetic Induction (TD EMI) and related techniques building on the results obtained from the CRREL iFROST mapping system. To achieve this goal, the following set of specific objectives has been identified:

1. Identify and measure major influencing factors (frozen state, mineralogy, moisture content, porosity, subsurface water, and environment) of the electrical resistivity of permafrost soils.
2. Determine the correlation between electrical resistivity and other physical and mechanical properties of permafrost soils using multiple measurement and analysis techniques.
3. Extend results to develop a portable truck-mounted system that integrates the sensor and analysis suite to complete a ruggedized PAMS combined with mapping tool interface.
4. Investigate the field performance of the truck-mounted PAMS compared with ground truth survey results obtained from alternative measurement methods, borehole, and other geophysical data.
5. Based on evaluation results, modify the portable PAMS to improve performance.
6. Provide guidelines and specifications on the suitability of the PAMS for mapping permafrost soil profiles.
7. Submit a final report summarizing all literature review results, device setup details, laboratory- and field-testing results, and recommendations.

RESEARCH PLAN

To fulfill the goals and objectives of this project, a comprehensive research plan was prepared and is proposed in this document. The proposed research plan consists of a total of six tasks.

Task 1. Conduct a comprehensive literature review

Task 1 involves a comprehensive literature review to synthesize information pertaining to the electrical resistivity/conductivity properties of soils under frozen and unfrozen states. In general, the literature search will cover research, standards, and practices pertinent to the electrical resistivity tomography of soil profiles and soil property characterizations based on electrical resistivity/conductivity results. The literature review will ensure that the research team identifies knowledge gaps and avoids any duplication of effort. All reviewed technical reports and papers will be documented, collected, and summarized into an electronic library and submitted to the research panel. Specific topics that will be addressed are:

1. Permafrost – The laboratory and field study of permafrost by other researchers will be reviewed. The physical (e.g., density, porosity, water content, shear wave velocity) and mechanical properties (e.g., strength, strain, modulus) of permafrost are of interest. The corresponding environmental conditions (e.g., temperature, ground water level, humidity) in cold regions will be explored as well.
2. Electrical resistivity/conductivity – The experimental measurement methods used for characterization of electrical resistivity and conductivity of soils will be researched, with emphases placed on the type of instrumentation employed, configuration of experiments, analysis of data, comparative investigation of the measurement methods, and the various soil property influence factors.

3. Geotechnical site investigation – Correlations between soil investigation results obtained from electrical resistivity tomography and those from other geotechnical site investigation techniques (e.g., SPT, DCPT, CPT) will be reviewed.

Task 1 Deliverable(s): A detailed report highlighting the findings of the literature review conducted as part of Task 1.

Task 2. Prepare and execute a laboratory testing plan

In this task, the research team will prepare and perform a comprehensive testing plan with the goal of evaluating the electrical resistivity change of permafrost with varying soil properties under cold region conditions. Tentatively, the proposed experiments will consider the following five factors: soil type, porosity, water content, pore fluid composition, and temperature.

1. Soil type – Seven representative soil types will be considered, covering both coarse-grained and fine-grained soils based on the AASHTO soil classification system.
2. Porosity – To determine the impacts of pore size on electrical resistivity, the research team will compact the soil to three different levels of dry densities.
3. Water content – The influence of water content in the soil will be investigated by considering three different water content levels.
4. Pore fluid composition – The electrical conductivity is related to the mobility of the ions present in the fluid filling the pores. Ion types and ionic concentration levels will be varied for testing.
5. Temperature – Ion agitation increases with temperature, resulting in lower electrical resistivity at high temperature. The testing temperature will cover room temperature (20 ^{o}C), 0, and -20 ^{o}C.

The research team will follow the ASTM D2166 standard to prepare 5 in (diameter) by 10 in (height) cylindrical soil samples. Electrical resistivity values will be measured for each soil specimen under different conditions and using different techniques. Correlations will be established between these factors and the electrical resistivity of soil.

Task 2 Deliverable(s): A report detailing the findings of the electrical resistivity range for soils with various physical properties at different temperatures.

Task 3. Develop a truck-mounted permafrost characterization system

This task involves the development of a portable system that mounts the PAMS to a construction truck. The process involves review of the data collection methods and results obtained from Task 2 to develop a modified data acquisition and data analysis system. This system is expected to be fabricated using the core data acquisition elements found to offer the best cost vs. performance trade-offs. This system will be lab tested to validate based on the same soil samples used previously. The final form of the PAMS instrumentation system will be engineered for the range of environmental conditions expected to be encountered during field applications. It is this system, which will be mounted in a purpose-built adapter to allow simple mounting/demounting on a vehicle. Once the mounting jig is developed, Time Domain EMI resistivity surveys will be conducted to collect data. The system will also incorporate a visualization/mapping (GIS) tool for viewing collected results in a spatial form. Geographical information such as location and altitude will be recorded in real time.

Task 3 Deliverable(s): A report documenting the development of the truck-mounted EMI system. A prototype that integrates Time Domain EMI and GIS systems will be made. Any challenges encountered during the prototyping process will also be discussed in the report.

Task 4. Conduct full-scale electrical resistivity surveying of permafrost at CREATEs

In this task, the research team plans to excavate a trench at the testing field of CREATEs. Trench dimensions will be determined based on experimental results obtained from Task 2 and numerical simulation predictions. The project team will discuss with the research panel to finalize the design. Trench will be thermo-insulated and sealed first, before being backfilled with soil of predetermined type and controlled physical properties (such as density, water content, pore fluid composition). Soil compaction will be controlled to reach the target dry density. The research team will attach a freezing panel to the top of the trench in order to lower soil temperature to cold region conditions. The spatiotemporal variations along the depth will be monitored through thermocouples installed at different depths. The permafrost characterization system mounted on the construction truck will perform an in-situ electrical resistivity survey of the trench. Soil mapping results will be compared against the known properties of testing soils in the trench.

Task 4 Deliverable(s): A report detailing the construction of a full scale permafrost trench and the performance of the prototype in permafrost characterization.

Task 5. Evaluate field performance of the permafrost characterization system

The goal of this task is to carry out field surveying of soil and validate the results against in-situ soil bore log results. The research team will adopt a two-step approach for site performance testing. In the first step, the research team will test the truck at two selected fields in New Jersey and test the overall performance of the system. Selection of the site will be based on discussions with the project's panel. The influences of operation condition (e.g., driving speed) and site environment (e.g., temperature, wind, ground surface, light condition) on survey results will be tested. The sites selected are expected to have detailed geotechnical profiles available from previous in-situ tests. Typical tests of interest include:

1. Standard Penetration Test (SPT) – SPT is an in-situ dynamic penetration test that provides an indication of the ground density.

2. Dynamic Cone Penetration Test (DCPT) – DCPT is similar to SPT in test and is performed by dropping a hammer from a certain fall height and measuring the penetration depth per blow.
3. Cone Penetration Test (CPT) – CPT provides a continuous profile of soil parameters including pore pressure, sleeve friction, and cone resistance.

Task 5 Deliverable(s): A report detailing the field performance of the truck-mounted EMI system and the suggested operation conditions and site environment for best performance.

Task 6. Prepare final report and recommendations

In this task, the research team will prepare the final report. The report will document all the results obtained as a part of this study. It will also include the literature review and recommendations regarding the usage of this device for permafrost characterizations.

OVERVIEW OF PROJECT SCHEDULE AND EFFORT

The length of the proposed project is 24 months including the 2 months for review and revision of the final report. The chart below provides an estimated timeline for task completion. Please note that Jan 2nd, 2020 was selected as the tentative starting date for this project.

Timeline of the proposed project

Task No.	2020												2021											
	Q1			Q2			Q3			Q4			Q1			Q2			Q3			Q4		
	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12
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REFERENCES

Andrews, R. J., Barker, R., & Heng, L. M. (1995). The application of electrical tomography in the study of the unsaturated zone in chalk at three sites in Cambridgeshire, United Kingdom. Hydrogeology Journal, 3(4), 17-31.

Archie, G. E. (1942). The electrical resistivity log as an aid in determining some reservoir characteristics. Transactions of the AIME, 146(01), 54-62.

Arulanandan, K., & Muraleetharan, K. K. (1988). Level ground soil-liquefaction analysis using in situ properties: I. Journal of Geotechnical Engineering, 114(7), 753-770.

Chambers, J. E., Wilkinson, P. B., Weller, A., Meldrum, P. I., Kuras, O., Ogilvy, R. D., ... & Penn, S. (2012). Characterising sand and gravel deposits using electrical resistivity tomography (ERT): case histories from England and Wales. Extractive Industry Geology Conference.

Chapman, W. L., & Walsh, J. E. (2007). Simulations of Arctic temperature and pressure by global coupled models. Journal of Climate, 20(4), 609-632.

Cooling L.F., & Marsland A. (1954). Soil Mechanics Studies of Failures in the Sea Defence Banks of Essex and Kent. Proc. ICE. - North Sea Floods 31 January/1 February 1953, pp. 58-73.

Dasog, G. S., & Shashidhara, G. B. (1993). Dimension and volume of cracks in a Vertisol under different crop covers. Soil science, 156(6), 424-428.

Dyer, M., Utili, S., & Zielinski, M. (2009). Field survey of desiccation fissuring of flood embankments. In Proceedings of the Institution of Civil Engineers-Water Management (Vol. 162, No. 3, pp. 221-232). Thomas Telford Ltd.

Gibert, D., Nicollin, F., Kergosien, B., Bossart, P., Nussbaum, C., Grislin-Mouëzy, A., ... & Hoteit, N. (2006). Electrical tomography monitoring of the excavation damaged zone of the Gallery 04 in the Mont Terri rock laboratory: Field experiments, modelling, and relationship with structural geology. Applied clay science, 33(1), 21-34.

Gunn, D. A., Chambers, J. E., Uhlemann, S., Wilkinson, P. B., Meldrum, P. I., Dijkstra, T. A., ... & Hughes, P. N. (2015). Moisture monitoring in clay embankments using electrical resistivity tomography. Construction and Building Materials, 92, 82-94.

Hoekstra, P., Sellmann, P. V., & Delaney, A. (1975). Ground and airborne resistivity surveys of permafrost near Fairbanks, Alaska. Geophysics, 40(4), 641-656.

Jones, G., Zielinski, M., & Sentenac, P. (2012). Mapping desiccation fissures using 3-D electrical resistivity tomography. journal of Applied Geophysics, 84, 39-51.

Jones, G., Sentenac, P., & Zielinski, M. (2014). Desiccation cracking detection using 2-D and 3-D Electrical Resistivity Tomography: Validation on a flood embankment. Journal of Applied Geophysics, 106, 196-211.

Keller, G. V., & Frischknecht, F. C. (1966). Electrical methods in geophysical prospecting.

Kleppe, J. H., & Olson, R. E. (1985). Desiccation cracking of soil barriers. In Hydraulic barriers in soil and rock. ASTM International.

Minsley, B. J., Abraham, J. D., Smith, B. D., Cannia, J. C., Voss, C. I., Jorgenson, M. T., ... & Deszcz‐Pan, M. (2012). Airborne electromagnetic imaging of discontinuous permafrost. Geophysical Research Letters, 39(2).

Morris, M. (2007). Management of flood embankments: a good practice review. London: DEFRA.

Overduin, P. P., Westermann, S., Yoshikawa, K., Haberlau, T., Romanovsky, V., & Wetterich, S. (2012). Geoelectric observations of the degradation of nearshore submarine permafrost at Barrow (Alaskan Beaufort Sea). Journal of Geophysical Research: Earth Surface, 117(F2).

Samouëlian, A., Richard, G., Cousin, I., Guerin, R., Bruand, A., & Tabbagh, A. (2004). Three‐dimensional crack monitoring by electrical resistivity measurement. European Journal of Soil Science, 55(4), 751-762.

Samouëlian, A., Cousin, I., Tabbagh, A., Bruand, A., & Richard, G. (2005). Electrical resistivity survey in soil science: a review. Soil and Tillage research, 83(2), 173-193.

Sentenac, P., & Zielinski, M. (2009). Clay fine fissuring monitoring using miniature geo-electrical resistivity arrays. Environmental Earth Sciences, 59(1), 205-214.

Thevanayagam, S. (1993). Electrical response of two-phase soil: theory and applications. Journal of Geotechnical Engineering, 119(8), 1250-1275.

Walker, M. D., Wahren, C. H., Hollister, R. D., Henry, G. H., Ahlquist, L. E., Alatalo, J. M., ... & Epstein, H. E. (2006). Plant community responses to experimental warming across the tundra biome. Proceedings of the National Academy of Sciences, 103(5), 1342-1346.

Wolken, J. M., Hollingsworth, T. N., Rupp, T. S., Chapin III, F. S., Trainor, S. F., Barrett, T. M., ... & Beever, E. A. (2011). Evidence and implications of recent and projected climate change in Alaska's forest ecosystems. Ecosphere, 2(11), 1-35.