Geotechnical Properties of Frozen Ground at McMurdo Station, Antarctica

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McMurdo Station is built on fractured basaltic frozen ground. The recent plans for the Station involve major buildings upgrades. Foundation design for the proposed buildings require understanding of the geotechnical properties. CRREL assisted in this effort by conducting a series of studies with a goal to improve geotechnical information. These included digging soil pits, radar profiles, laboratory tests and coring data. Radar surveys conducted up to 10 m depth identified the active layer, permafrost, excess ice, fill thickness, solid bedrock depth, buried utilities, construction and waste debris. Visual profiles from the soil pits were quantitatively corroborated with insitu samples for gradation, moisture content and density tests. Ground profiles indicated a very shallow active layer exists at a maximum depth of 30 cm in the undisturbed ground and 60 cm in the anthropogenic fill, with segregation ice at the bottom from seasonal snowmelt. The undisturbed natural deposits are composed of fractured basaltic boulders, rocks, gravelly sand, and ice. The ice-cemented course-grained materials (less than 300 mm in size) of gravelly sands exist due to sedimentation. Ground ice does occur in these irregular interbedded strata with different cryostructure formation to the Arctic terrains. The lack of precipitation and groundwater generally prevent large-scale development of wedge ice. Laboratory tests from the uniaxial compression tests on remolded frozen gravels tested between 4% and 20% ice content resulted in compressive strength from 0.6 to 1.6 MPa at −7°C and from 2.7 to 6 MPa at −20°C. If these strength values meet the requirements, we can reliably expect for the ice-poor to ice-free volcanic rock to be stable specially as temperatures drop. However, snow, ice from meltwater deposit, and possible debris were anthropogenically buried with fill materials for flat areas. Ground ice or any thaw unstable materials must be removed, especially for shallow footers foundation design options.

Thaw consolidation model for permafrost based on the residual stress

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The concept of the residual stress has been introduced by Morgenstern and Nixon (1971). It has been defined as the effective stress existing in the soil skeleton when a fine-grained soil is thawed under undrained conditions. In practice, this definition has mostly been applied to bulk soil sample which is only theoretically valid for ice-poor soils. The definition of the residual stress can be generalized to include ice-rich soils by specifying that the residual stress is the effective stress within the soil elements upon thawing rather than the effective stress in the bulk soil. This definition is in theoretical agreement with the historical definition of the residual stress and it allows to distinguish between the thaw consolidation behaviour of excess ice and of the soil skeleton while using a unique void ratio – effective stress relationship. Morgenstern and Nixon suggested that the residual stress could be an intrinsic soil property. The practical implications of the residual can thus be extended to the development of empirical relationships based on the residual stress. Empirical relationships are developed for the compression index of the thawed soil, the residual stress, the hydraulic conductivity change index of the thawed soil and the initial hydraulic conductivity of the thawed soil. The liquid limit, the clay content and the median grain size of the fine fraction are used as predictive parameters. The median grain size of the fine fraction offers the greatest precision.

Measurement Techniques for Soil Freezing Characteristic Curves

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Soil freeze/thaw processes play a role in the hydrology, geophysics, ecology, thermodynamics and soil chemistry of permafrost systems. In these processes, the temperature of the soil is related to the soil ice content through a soil freezing characteristic curve (SFCC). This mathematical construct relates the soil ice content to a specific temperature for a particular soil. SFCCs depend on many factors including soil properties, soil pore water pressure, dissolved salts, (hysteresis in) freezing/thawing point depression, and degree of saturation, all of which can be site-specific and time varying. This has led to the development of many diverse SFCCs for applications in different study sites, fields of study and for differing research purposes. As climate warms, much of the earth's frozen ground warms and approaches the freezing/thawing temperature where the choice of SFCC becomes more important, especially in modelling studies that predict changes in ground ice content.

Many SFCCs are empirically based and rely on collection of freezing and thawing data for the soil in question. Short of this, SFCCs based on theory alone are highly dependent on soil properties. In many watersheds, these detailed data are not available, and yet hydrological and geophysical models are still necessary and depend on soil freeze/thaw processes. To address this, a synthesis of measured SFCC data from literature is organized into an open-source compilation for the available range of studied soils. Data digitized from previous (historic) lab and field measurements is gathered, and data collection methods are compared. The theoretical basis of each measurement technique is described. Uncertainty bounds are estimated for each measurement technique based on the aggregate data. Future work understanding the propagation of this uncertainty in modelling and creating a data processing tool is outlined.

Fine-scale heterogeneity vs. large-scale models: Effects of soil heterogeneity on simulated physical properties - Does it matter?

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Soil texture, i.e. its composition of clay, silt and sand, as well as organic material, is often very heterogeneous within small distances. State-of-the-art land-surface models usually cannot capture this due to their coarse grid. However, neglecting small-scale soil heterogeneity may affect the estimated exchange of energy, water, and carbon between land and atmosphere strongly.

This discrepancy is especially problematic when modelling permafrost soils, where the heterogeneity-induced mismatch can make the difference between frozen and unfrozen soil, or waterlogged and unsaturated soil, as soil texture determines physical properties such as heat and water-storage capacity. By that, soil heterogeneity affects the build of soil ice and resulting frost heave, determines pond locations, and ultimately influences soil genesis, e.g. by inducing cryoturbation. The determination of soil geophysics also propagates into biogeochemical dynamics, affecting the Arctic carbon cycle by providing the environment for either carbon stabilization or degradation.

To assess the effect of soil heterogeneity in detail, and quantify the potential mismatch, we develop a two-dimensional geophysical soil model with a spatial resolution of less than 10 cm at the region of interest. We apply our model at permafrost sites, because our ultimate aim is to understand cryoturbation as a permafrost-specific soil process and its relevance for the Arctic carbon cycle, which will finally allow us to improve predictions of the Arctic carbon budget.

Here we present our first results, where we study the effect of fine-scale soil heterogeneity on physical properties, i.e. soil temperature, water, and ice, that directly affect the sensible and latent heat fluxes between soil and atmosphere. By comparing simulations with and without soil texture heterogeneity, as well as with and without lateral fluxes of heat and moisture, we are able to quantify the effect of soil heterogeneity at small scale and discuss the effect on larger scales.

Permafrost core characterization using gamma ray attenuation and industrial computed tomography scanning

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The physical properties of permafrost cores are largely measured using destructive methods. These approaches are time-intensive and sacrifice critical samples collected at great expense. The development of rapid, non-destructive methods to quantify permafrost physical properties shows great promise, but is still poorly developed. In this study, we assess the potential of gamma ray attenuation and industrial computed tomography (CT) scanning to measure physical properties, including density and volumetric ice content, in a range of permafrost cores in the newly developed Permafrost Archives Laboratory at the University of Alberta. We describe the development of calibration standards and individual capabilities for both a GEOTEK multi-sensor core logger (MSCL; including imaging, magnetic susceptibility, non-contact resistivity and gamma density), and a Nikon XTH 225 industrial micro CT scanner. These results are compared with established destructive methods for permafrost-core analyses. The MSCL has a higher throughput capacity, and lower cost per metre of core, compared with the micro CT scanner. MSCL, once calibrated, shows the potential for processing 10s of metres per day to generate high quality images, magnetics and density data. Gamma density data is broadly comparable with CT-generated density measurements (derived from linear attenuation of x-rays), but represents a narrow transit of the core compared with the potential for whole core analyses via CT scanning. CT scanning still remains one of the most useful tools, but is limited by the relatively high costs and time required to image cores. We have found that a combination of MSCL for the rapid characterization of cores, complemented by detailed CT imaging and quantitative analyses, provides a useful approach for permafrost projects in our laboratory.

Material properties of advanced high-strength cold-formed steel alloys subjected to subzero temperatures

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Advanced high-strength cold-formed steel alloys (AHSS) have been developed and due to advancements in chemical composition, multiphase microstructures, and other micromechanical changes, AHSS have three to five times the strength of conventional mild steels with yield strengths up to 1250 MPa and ultimate strengths up to 1900 MPa. Originally developed for automotive applications, AHSS have a high potential for application into the building construction industry. For the eventually use of AHSS for structural engineering in cold climates, the material properties must be properly quantified. An experimental investigation was carried out for a series of tensile coupon tests on three different AHSS alloys consisting of one dual phase steel with a nominal yield strength of 580 MPa and two martensitic steels with nominal yield strengths of 1030 MPa and 1200 MPa, in addition to two conventional cold-formed steel alloys consisting of one high-strength low-alloy steel with a nominal yield strength of 700 MPa and a mild steel with a nominal yield strength of 395 MPa, which served as a reference. The test temperatures ranged from ambient to -60°C at an interval of 20°C following the steady-state test protocol for testing at subzero temperatures. The stress-strain relationships and important material properties, including elastic modulus and stresses and strains at the yield, ultimate, and fracture points, were obtained from the tensile tests using an extensometer. Additionally, a grid method was adopted to measure the fracture elongations under various gauge lengths. The results demonstrate that AHSS have larger yield and ultimate strengths and fracture elongation at subzero temperatures than at ambient and no significant decrease in the elastic modulus was observed, indicating the high potential for adopting AHSS as a building construction material in cold climates. Furthermore, a series of predictive equations on key material properties and stress-strain relationships at subzero temperatures were developed.

An Experimental Investigation of Coupled Thermo-Dielectric Properties of Icy Porous Media

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The freezing temperature of water in porous media is not constant but varies over a range determined by the structural properties of materials. Consequently, the amounts of unfrozen water and ice change with temperature in frozen conditions and varying temperatures, which in turn affects thermal and mechanical properties. Quantification of ice coverage and water content in porous material is challenging. One approach is to indirectly determine from dielectric constant of the porous material using techniques based on electrical measurements.

In this study, we first aimed to detangle the coupled phenomena to understand the interactions between thermo-electrical processes to characterize the coupled thermo-dielectrical properties of a porous material at different scales using two different approach: Time Domain Reflectometry and Impedance Spectroscopy. We performed element-scale and tank-scale experiments to measure dielectric constant of reconstituted inorganic porous material in the laboratory at varying initial water content and temperatures. Although the two methods operated in different frequency ranges, the data generated from these experiments were comparable. The dielectric constant increased with increasing temperatures until all the ice in the pores thawed at different temperatures. The results indicated that the dielectric constant of the porous silt increases with the decrease in frequency. This is due to the increased electrical conductivity of water when it is exposed to a low frequency alternating current. The results from these experiments not only allow us to characterize the response of porous materials with changing environmental conditions, but also relate the length scales for thermo-dielectrical properties.

Creep of marginally frozen soils

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Creep of road embankments is a recurring problem in permafrost regions. Important degradations such as shoulder cracking and rotation reduce the functional capacity and lifespan of embankments, which considerably increases the maintenance costs of these structures. The problem, fairly well documented in the literature, is generally attributed to the static weight of the embankment on the underlying permafrost. However, degradations likely due to creep were observed on some portions of the Alaska Highway in Yukon, where the embankment is rather thin. Virtually no documentation is available on creep of thin embankments. Furthermore, little information is available on the effect of the passage of heavy vehicles circulating

on these embankments. The main objective of this project is to quantify the effect of repeated loading on the mechanical behaviour of marginally frozen soils. A new method was developed to conduct static and dynamic creep tests on frozen soils in a triaxial cell. The main innovations are the optimized control and acquisition of temperature around the sample, and the possibility to conduct drained tests. Creep tests were carried out on reconstituted ice-rich clay. The temperature varied between -3 and -0.5 °C, which simulated the behaviour of a warm permafrost. Deformations

caused by static and dynamic loading were treated separately, so that a method could

be developed to estimate settlements caused by building a 1 meter embankment on the one hand, and settlements caused by the passage of heavy vehicles on the other hand.

Synthesis of Geophysical and Geomechanical Properties of Permafrost-Affected Soils Highlights Complex Processes of Permafrost Degradation in a Geotechnical Context

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Recent permafrost degradation across the high northern latitude regions has impacted the performance of the civil infrastructure. This study summarizes the current state of physical processes of permafrost degradation in a geotechnical context and the properties of permafrost-affected soils critical for evaluating the performance of infrastructures commonly built in the high northern latitude regions. We collected a total of 92 datasets with 3027 data points from 37 journal and conference publications and analyzed the variations of geomechanical and geophysical properties under the effects of permafrost degradation. The datasets represent a range of geomechanical and geophysical properties of permafrost-affected soils with different soil types and compositions under different testing conditions. While the data collected are highly scattered, regression analysis shows that most geomechanical and geophysical properties have strong associations with temperature. These associations highlight that ongoing warming will greatly affect the performance of civil infrastructures at high northern latitudes. These properties include elastic moduli, strength parameters, thermal conductivity, heat capacity, unfrozen water content, and hydraulic conductivity. This paper also discusses other factors, such as soil type, soil composition (e.g., total moisture content, porosity, bulk density, and salt content), and confining pressure, which may further complicate the relationships between temperature and the geomechanical and geophysical properties. Through this review, we identify key knowledge gaps and highlight the complex interplay of permafrost degradation, temperature, soil heterogeneity, and soil geomechanical and geophysical properties. Given the scarcity of certain permafrost properties in addition to the complex processes of permafrost degradation in the geotechnical context, there is a need to establish a comprehensive and curated database of permafrost properties. Hence, we encourage broader collaboration and participation by the engineering and scientific communities in this effort.