Innovations in Permafrost Ground Ice Characterization

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Perennially frozen ground, also known as permafrost, consists of soil, rock, and ground ice, which can provide rigid base material suitable for the foundation of Arctic infrastructure. Permafrost is defined as soil or rock with a temperature that remains below 0 °C for two or more consecutive years (French, 1980). Globally, permafrost affects approximately 24% of Earth's land areas, where approximately 85% of Alaska is permanently frozen. Utilizing unique engineering methods, permafrost has successfully supported many different types of infrastructure, both vertical (e.g., buildings, towers, and fuel or water tanks) and horizontal (e.g., roadways, runways, pipelines). The local distribution of permafrost is affected by geographical properties such as soil types, organic layers and vegetation cover, surface albedo, topography, and surface water conditions. Permafrost areas are classified according to the extent of the frozen ground: *continuous* – where permafrost exists continuously both laterally and to great depths, *discontinuous* – areas of frozen and thawed ground, *sporadic* – where frozen ground is infrequently encountered, or *isolated* patches. Permafrost terrain typically consists of three layers. The top layer, also called the active layer, undergoes seasonal thawing and freezing. Below the active layer permafrost is encountered, which by definition has a temperature constantly below 0 °C. Due to the geothermal heat flux, permafrost has a lower boundary, below which the ground is again unfrozen.

The ≤0°C temperature threshold that defines permafrost is not the engineering challenge *per se*. Rather, it is the configuration and amount of ground ice, or cryostructure, within the near-surface permafrost on which the infrastructure will be situated. Ground ice frequently occurs as massive bodies of ice, often greatly exceeding the usually modest amount of ice that is found in the pore spaces of the soil matrix. These massive bodies of ground ice can occur as thick layers of segregation ice that are many centimeters in thickness and meters in lateral extent. This segregation ice occurs due to the movement of the freezing front, orthogonal to the surface and into the soil column where matrix water is drawn to the freezing front creating tabular ice generally parallel to the surface. Massive ice can also occur as polygonal networks of large ice wedges which often are meters in width and depth, and tens of meters in length. The mode of permafrost formation and the length of time since permafrost establishment in large part determines this ground ice character. In general, permafrost terrains are extremely heterogeneous in ground ice character, often varying in ice content by an order of magnitude or more over horizontal extents of just meters. It is this heterogeneity that most significantly governs the type of engineering solution to be used when supporting infrastructure (Melvin et al, 2017).

Proper engineering for long lasting and maintenance free permafrost infrastructure requires sufficient knowledge of the amount and distribution of ground ice. Melting of the ground ice causes volume displacement within the soil mass, subsequent settlement at the surface, and weakening of the soil-bearing capacity due to excess water. Therefore, thaw settlement or subsidence varies spatially according to the distribution of the ice content. When the permafrost below infrastructure thaws, subsequent settlement is enhanced by the infrastructure itself, inducing uneven thaw strain and causing cause damage to buildings (e.g., cracks in walls and warping of floors). In ice-rich ground, thaw may also affect drainage conditions and result in soils with very high water saturation; such soils are more vulnerable to active-layer detachments. Some locations may be ice-poor or even ice-free, requiring minimal augmentation of standard design. Ice-rich locations, on the other hand, require a substantial expenditure in foundation and structural elements to ensure adequate resistance against settlement and increase the longevity. Often refrigeration is employed, either in a passive mode via ambient air ducting and structure elevation above the ground surface, or with active freezing mechanical systems, which are significantly more costly and require intensive maintenance.

Figure. 1. A large ice wedge (triangular feature in the center between the two people) exposed in the Cold Regions Research and Engineering Laboratory Permafrost Tunnel near Fairbanks, Alaska. The ice wedge is nearly 100% pure ice intruded into wind and slope deposited silt.

Figure. 2. Thaw settlement associated with an airfield in Greenland. Thawing of ice-rich, weathered bedrock at approximately 2 m below the surface is causing severe settlement, resulting in the need for significant maintenance measures to continue operations.

Permafrost encompasses a tremendous variety of inter-dependent permafrost and terrain conditions. These widely variable properties determine or affect its response to thermal changes and thus the performance of foundations and cycles of impact and feedback between foundations and permafrost (Baumann et al, 2017). This is especially important as development of the Arctic continues; and key U.S. Federal agencies, such as DoD, will be establishing facilities in these remote locations (Hinkel et al. 2003).

Understanding the complex nature of permafrost and surficial properties is central to foundation engineering and to mitigating potential future impacts to built infrastructure. Key parameters affecting performance for infrastructure engineering are ground ice extent and quantity (gravimetric moisture content), soil type, material properties (both frozen and upon thawing), active layer thickness, ground temperature, and thermal profile (Johnston 1981). Properties linked with these factors include the texture of the material (which influences pore ice content) and highly complex distributions of massive bodies of ice (ice wedges and sills, large lenses, thin discontinuous layers, and segregation ice).

To minimize both risk and cost, there is a need to fully interpret the heterogeneous conditions in a cogent manner and to apply a sophisticated approach to characterizing a potential infrastructure site. The standard method for geotechnical sampling of permafrost soils is borehole drilling, most often to modest depths of 10m to 15m, with varying borehole spacing according to the infrastructure use and type (i.e. vertical or horizontal). Simply drilling at regularly spaced intervals or in a more unsystematic manner is the routine method, resulting in costly procedure that may only be partially informative. Each borehole provides information about only a single point location, and drilling multiple geologically random holes often completely misses critical variability and spatial relationships between boreholes. Additionally, it often does not specifically capture the boundary zones where critical permafrost-bearing capacity changes occur.

However, at the same time, boreholes provide indispensable exploratory and confirmatory site data that absolutely must be collected; so the key is a strategic, comprehensive approach, maximizing the value of a minimal number of deliberately placed boreholes with some level of interpretation between the boreholes. Ancillary data to inform borehole placement and to enable comprehensive analysis can be acquired through multiple primary methods and sources, including aerial and satellite imagery, geophysical measurements, geologic and topographic maps (including digital elevation models, DEMs), and geospatial statistical analysis. In some cases, other high-resolution data is obtained through aerial or drone surveys, such as LiDAR and three-dimensional photography. Ideally, site analysis should be approached as an iterative, multi-disciplinary process, building progressively on knowledge gained in each previous step and synthesizing data from each of the surface and subsurface characterization techniques and analyses. The first step is a background analysis of existing imagery of the site, which can provide information on terrain, landforms, vegetation, and hydrologic features, from which some preliminary understanding of permafrost distribution might be gained. If geologic investigations have been completed, however general, they will provide information on the subsurface geology and may include other data such as permafrost depths or ice distribution. Landforms or terrain units are often identified as part of such investigations, usually including a general description of their subsurface structure and sedimentology.

To augment the borehole mapping analysis, surface based geophysical methods should be employed to obtain data between the borehole locations. Frozen earth materials are resistive to electric current flow, particularly those with appreciable ground ice content, and this frozen ground characteristic is used to provide spatially continuous mapping of ground ice content. Typical values are: 0 to 100 ohm-m responses often indicate thawed, potentially wet materials; 100 to 1,000 ohm-m responses often indicate generally ice-poor, frozen coarse-grained material such as sands and gravels; and 1,000 to 100,000 ohm-m responses often indicate ice-moderate to ice-rich materials (Hoekstra 1975). Another useful geophysical tool for permafrost characterization is ground penetrating radar (GPR). Here radar wave energy is transmitted into the subsurface, and changes in velocity are measured of the transmitted and returned signal. The changes generally occur due to differing dielectric permittivity from one substance to another, such as the contrast in electrical phase changes produced when the energy travels through thawed soils into frozen, or when traveling through ice poor soils vs. ice rich.

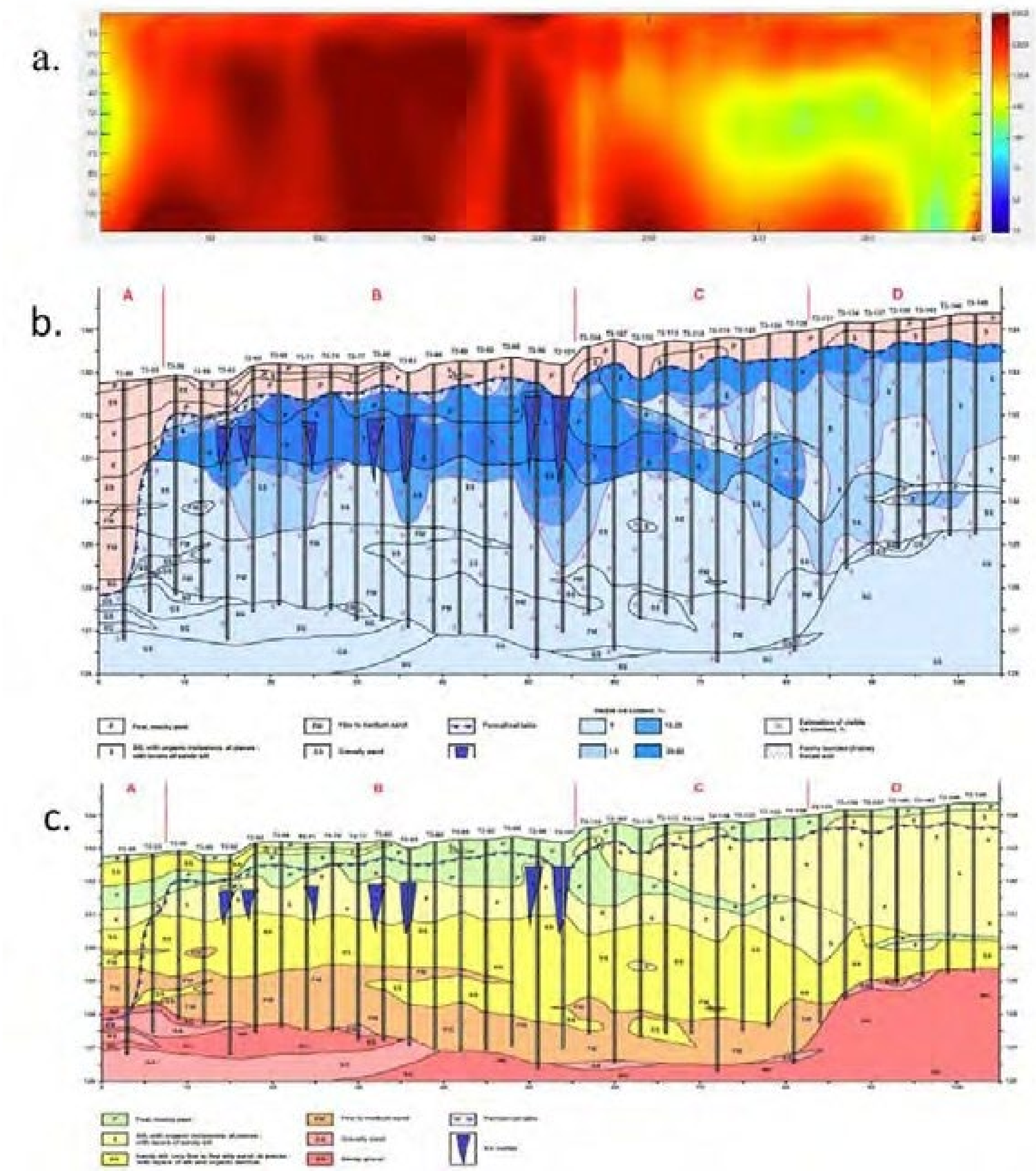


Figure 3. Stacked comparison of transect results: (a) Resistivity profile along the track of borehole locations, (b) borehole core analysis derived subsurface permafrost map, (c) and soil conditions from interpretation of borehole core analysis. Borehole locations are overlaid on the permafrost and soil condition profiles.

An extensive investigation was conducted in Fairbanks, Alaska at three locations, all of varying permafrost soil types and ground ice character. At the Cold Climate Housing Research Center (CCHRC) an 80m transect was surveyed utilizing earth resistivity methods, and drilled extensively every 3m along the transect, and sampled every 30cm to a uniform depth of 8m. Cross-sections illustrating comparison of resistivity results to ground ice content and soil type is shown in Figure 3. The value to engineering determinations is illustrated in Figure 4.

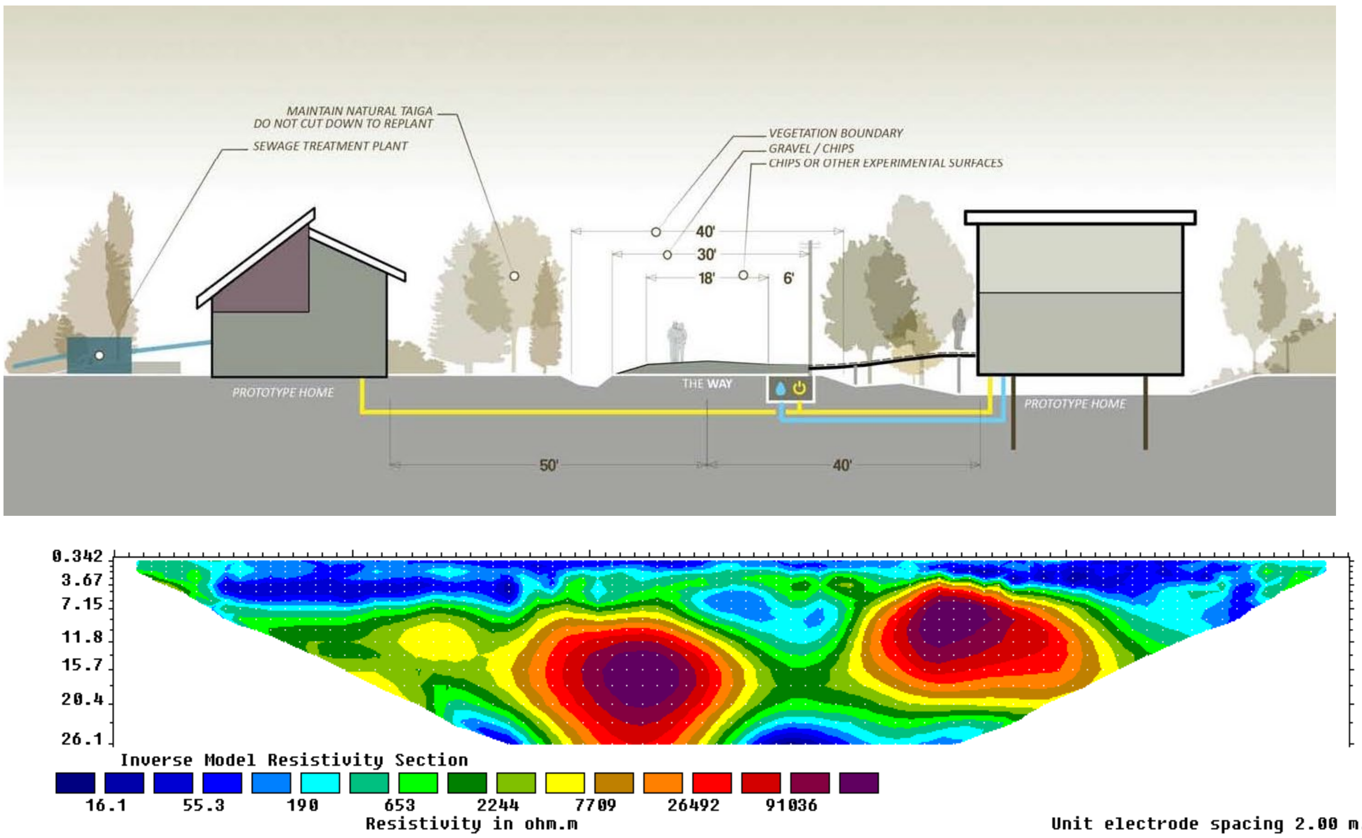


Figure 4. Cross-section of resistivity data for permafrost soils beneath student housing at CCHRC. The structure on the left is to be constructed slab-on-grade over ice-poor permafrost as shown in the lower resistivity plot (blue and green). While the structure on the right is to be constructed on piles for ambient air cooling over ice-rich permafrost (oranges and red)

For an actual construction example, the resistivity method was used at Thule Air Base, Greenland to investigate the 3000m long, flexible pavement runway, which had long been plagued by continued thaw settlement of permafrost soils (Bjella, 2013). To protect the permafrost from seasonal thaw for the last 50 years, annual white painting had been conducted of the 370,000m^2 of airfield pavement, causing maintenance and aircraft safety problems. The ice rich zones were successfully delineated via resistivity surveys (Figure 5) to identify the boundaries of the thaw sensitive areas, providing very specific solicitation information for buried insulation installation during the recent repaving of the entire airfield.

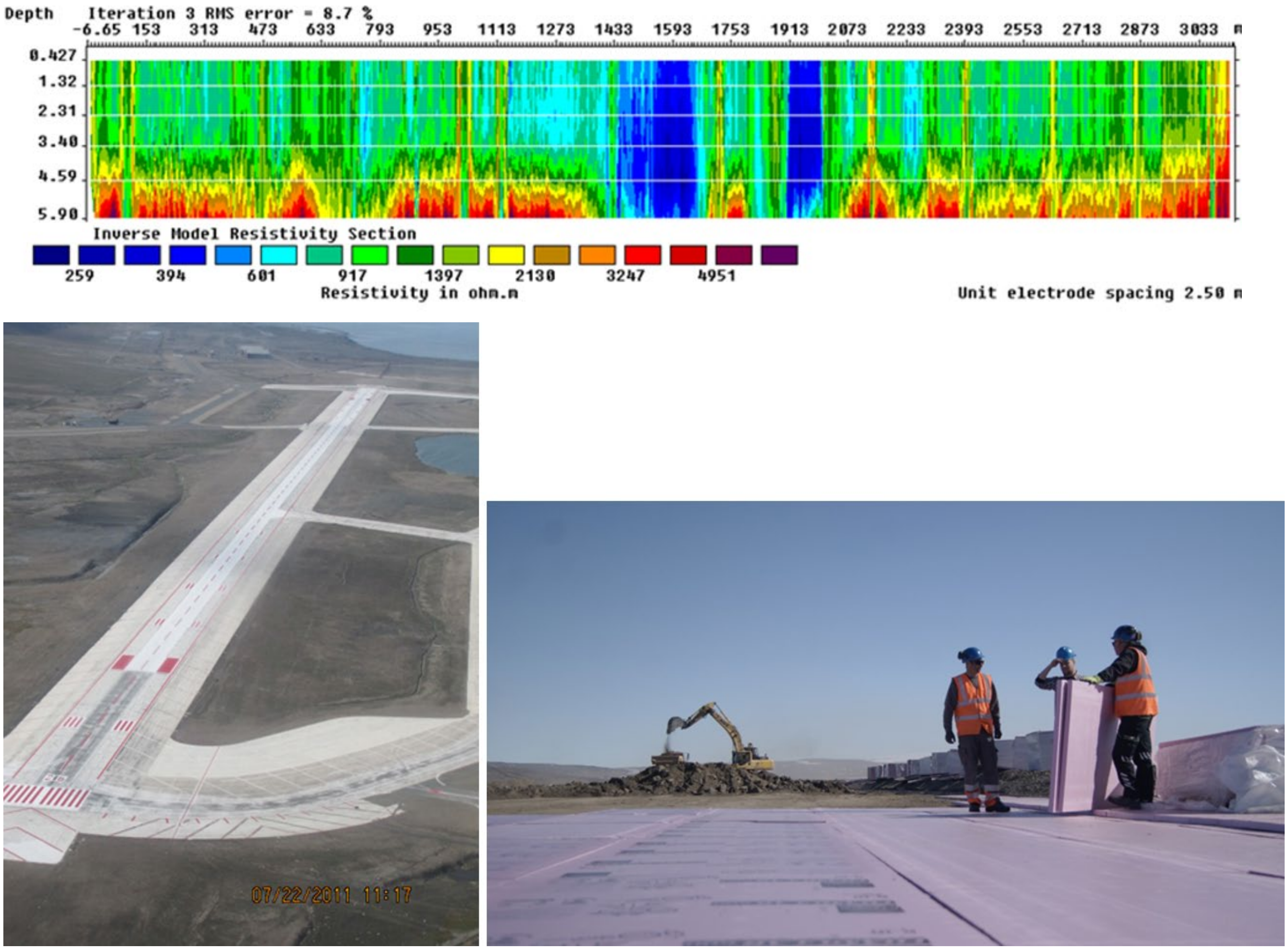
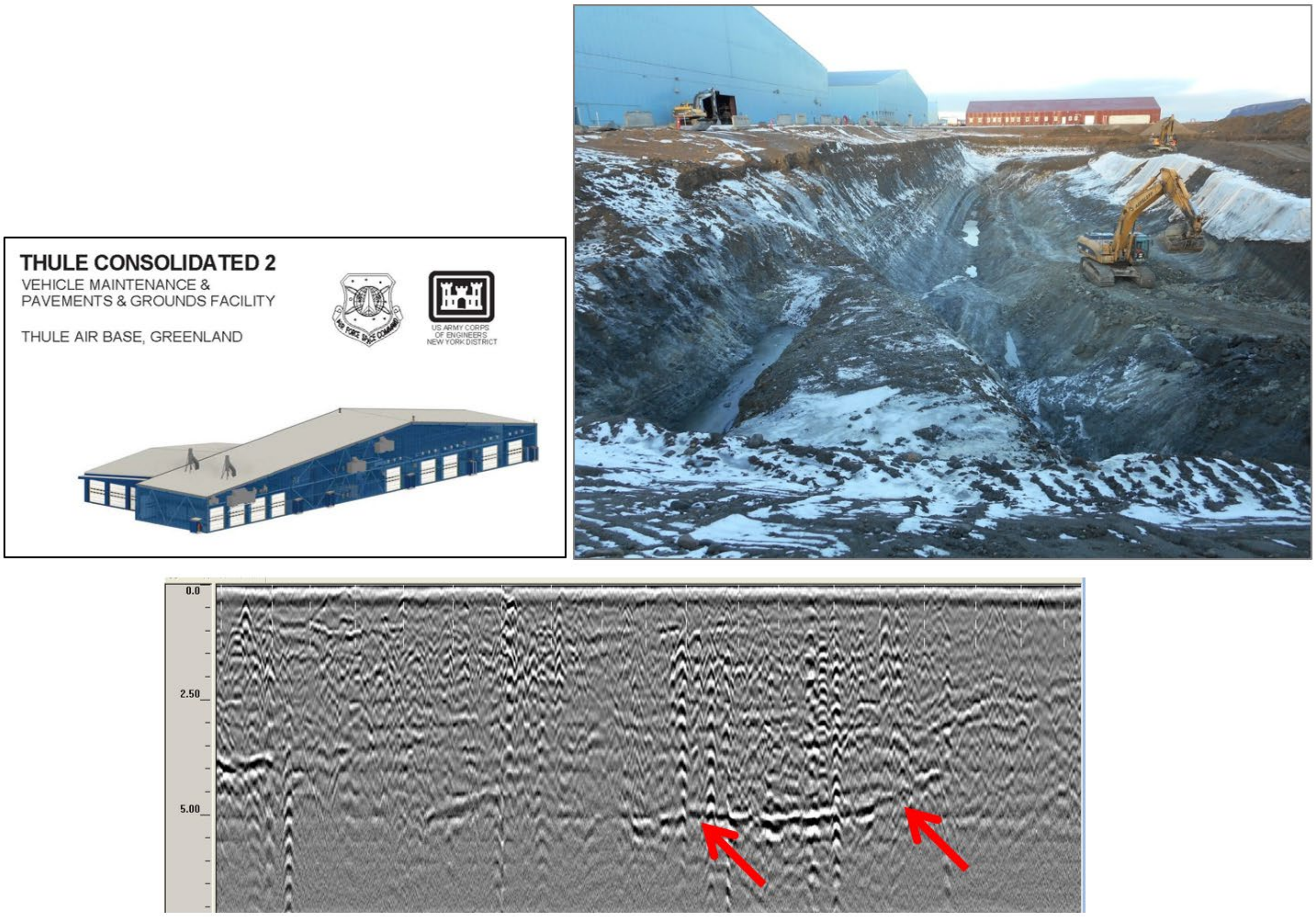


Figure 5. Determination of ground ice extent Thule Air Base, Greenland. (a) resistivity profile of the runway. Blue areas indicate near surface conductive bedrock prone to excess ice with thaw settlement and surface depressions. (b) white painted runway surface prior to repaving to offset permafrost degradation. (c) installation of extruded polystyrene insulation board for 600m of thaw sensitive runway embankment.

In another example, GPR allowed for an robust construction method by over-excavating the ice-rich sediments, down to ice-poor/ice-free competent bedrock. Over-excavation has an economical threshold of balancing the cost of excavation and the placing of large quantities of fill material, against the costs of increased structural costs for elevating to create an air space or the high cost associated with the use of heat pipes (thermosyphons). When over-excavation is cost efficient, one great benefit is that the structure site is now free of troublesome ground ice and thus becomes climate change neutral, and the site is now conditioned for future structures as well. GPR specifically provided accurate depth to the boundary between ice-rich (thaw-unstable) and ice-poor (thaw-stable) sediment/rock. Precise volumes could then be calculated to make the cost/benefit analysis (Figure 6). This mode of permafrost foundation prepares the site for perpetuity, and is the first of its kind for Thule AB (Bjella, 2012).



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