EXECUTIVE SUMMARY

Improving Design Methodologies and Assessment Tools for Building on Permafrost in a Warming Climate

SERDP Project RC-2436

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ACRONYMS AND ABBREVIATIONS

CCHRC	Cold Climate Housing Research Center
CCR	capacity coupled resistivity
CRREL	Cold Regions Research and Engineering Laboratory
DDF	Development Difficulty Factor
DoD	Department of Defense
DTS	distributed temperature sensor
ERDC	Engineer Research and Development Center
ERT	electrical resistivity tomography
EWDS	Early Warning Detection System
GIS	geographical information system
GPR	ground-penetrating radar
LiDAR	Light Detection and Ranging
MAAT	Mean Annual Air Temperature
PFFDSS	Permafrost Foundation Decision Support System
RTF	Research and Testing Facility
SERDP	Strategic Environmental Research and Development Program
USGS	U.S. Geological Survey

1.0 INTRODUCTION

The Arctic and Sub-Arctic have been key regions of geopolitical concern since World War II, and continue to have strategic importance for the Department of Defense (DoD). A vast majority of the region is characterized by permafrost landscape. Because landscape dynamics influence the physical and biological processes within the terrain, military installations must over-come many challenges related to their infrastructure, facilities, and other logistical operations located throughout most of the permafrost regions. The physical properties of the permafrost landscape can differ vastly depending on its soil and ground ice content characteristics, even within relatively short distances. These permafrost properties are critical in determining land-scape responses to disturbance from construction activities, infrastructure emplacement, and mobility operations.

Another part of the landscape dynamics is the permafrost subsidence, which is primarily related to the phase change of ground ice to water at or near to 0 °C and to the soil thermal regime changes due to human activity, infrastructure emplacement, or systemic shifts related to weather and climate. Such subsidence may be rapid and catastrophic (within days), very slow and systematic (over decades), or potentially intermediate (over months or years). These changes to permafrost can notably increase risks to the structural stability of critical built infrastructure, often by shifting, cracking, and otherwise damaging foundations and buildings. Such damage requires costly mitigation that disrupts planning, operations, and budgets.

DoD guidelines for effective construction of infrastructure on permafrost landscapes have exist-ed for decades. Construction in this environment is commonly built to high standards requiring multi-decadal longevity. Designers apply these guidelines first by accurately characterizing up-per permafrost and surficial properties at specific building locations, then by carefully evaluating foundation options based on cost and risks, and finally by making an informed selection from the most appropriate construction techniques. The first step is crucial. The location of an infrastructure suitable to a given site and selection of the best foundation construction approach requires a comprehensive investigation to assess the conditions of the entire building footprint from the surface down to the effective engineering depth. In reality, the hard constraints of timing, budgets, and logistics prevent practitioners from conducting such complete assessments. The consequent lack of comprehensive assessments can result in costly overbuilt construction that accounts for unknown permafrost conditions, or construction that allows undue risks to the stability and integrity of critical DoD infrastructure. In either case, a substantial amount of sub-surface information is necessary to minimize construction cost (i.e., reduce the tendency to overbuild in permafrost-affected regions) while ensuring long-term integrity.

Currently and in the foreseeable future, the needs for DoD design and construction dictate that design and engineering work be distributed among personnel with a mix of experience, with a range of institutional knowledge of effectively design and construction on permafrost landscapes, from highly experienced experts in permafrost construction to less experienced individuals with the appropriate engineering backgrounds. Engineers new to permafrost can benefit from direct guidance and assistance in site assessment and design selection, while the more experienced engineers can increase efficiency by contributing more refined site assessment approaches. This holistic approach addresses the knowledge gap for both site assessment and de-sign selection, and benefits practitioners at all levels of institutional knowledge of permafrost. Strategic Environmental Research and Development

Program (SERDP) project RC 2436 seeks to address these gaps to maximize the resilience of built infrastructure constructed on perma-frost, under existing conditions and also under conditions of increased future risk associated with climate change.

2.0 OBJECTIVES

The objective of the study was to provide a process or guide for site assessment and design selection using holistic methods. The methods required various steps and activities (Figure ES-1), as follows: (1) choosing the optimal location for infrastructure within a given site, (2) compiling existing information and acquiring data for determining promising foundation alternatives, (3) developing finite-element thermal modeling parameters for estimating foundation impacts to permafrost, and (4) assessing long-term monitoring options for identifying threats to infrastructure early on, while they can best be mitigated.

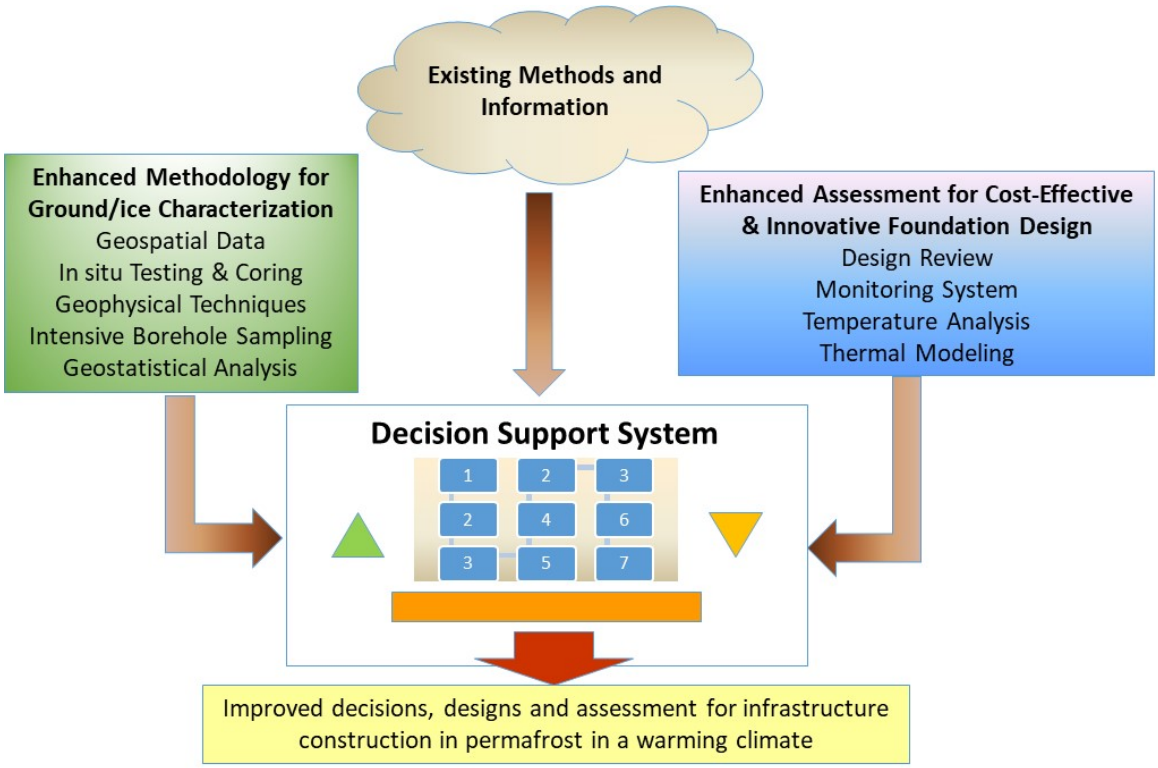

Figure ES-1. Flowchart Illustrating the Integrated Approach Used in the Study.

This research used emerging technologies, higher resolution information, and models to provide statistically supported, theoretical underpinnings for a system that both enhances the effectiveness of site assessment in permafrost regions, and reduces the effort and cost associated with that activity. A further goal that emerged from this study was to develop a holistic approach that provides the knowledge to guide engineers new to permafrost in permafrost reconnaissance while offering spatially explicit data storage and visualization options to seasoned permafrost engineers, ultimately facilitating the most efficient and cost-effective result.

3.0 TECHNICAL APPROACH

To develop this systematic methodology, three test sites (Cold Climate Housing Research Center [CCHRC], CRREL Permafrost Tunnel, and CRREL Farmer's Loop Test site) that represent various ranges of permafrost conditions and terrain in Interior Alaska were studied for site characterizations. Various tools and methods were used at the three sites to effectively characterize the subsurface information of the permafrost. Ancillary data for background information of the sites such as aerial photos and Light Detection and Ranging (LiDAR) imaging revealed details of terrain, vegetation cover and type, and surficial features that suggest geologic origins, ground ice presence (polygonal ground), drainage, and other characteristics. Surface terrain features can indicate whether (or not) permafrost exists at depth. Geophysical instruments for continuous subsurface transects were conducted using electrical resistivity tomography (ERT), capacity coupled resistivity (CCR), and ground-penetrating radar (GPR). Figure ES-2 shows an example of CCR surveys that reveals (in dark red colors) distinctive ice content features along each transect. The borehole data and geophysical measurements provided the variation of permafrost or its ice content as a function of depth or areal extent. The ground soil type, the frozen or unfrozen state of the ground, and moisture content from the borehole core data provided the physical information to improve the correlation between ground resistivity and subsurface conditions at the specific location of interest.

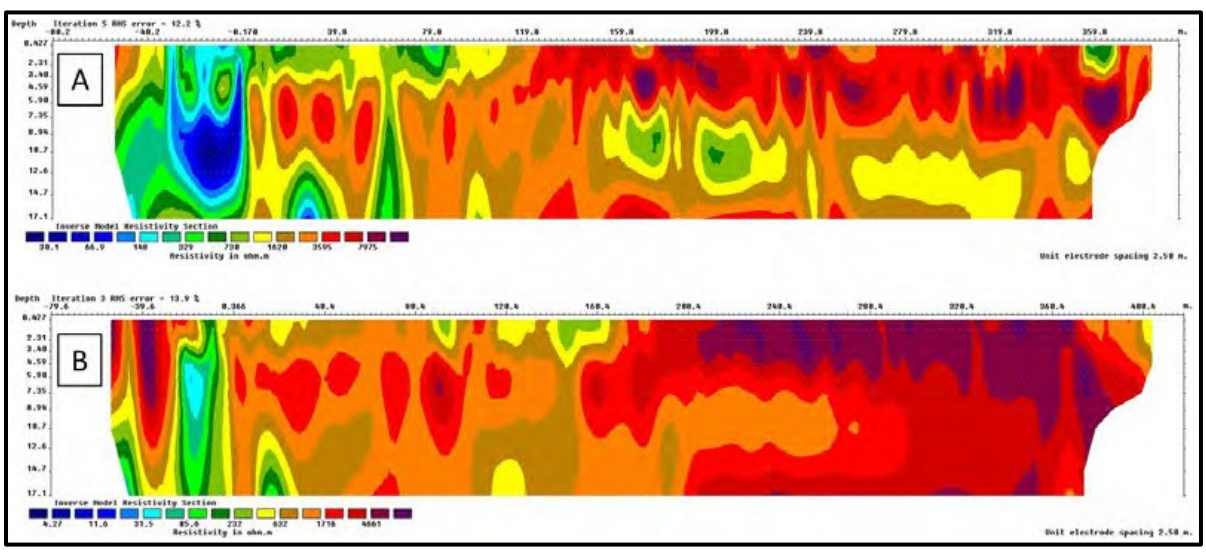

Figure ES-2. Resistivity Profiles Along Two Transects at the Farmers Loop Site Indicating (in dark red) Pockets of High Ice Content in the Ground.

A geostatistical analysis based on a Bayesian Gaussian model using the surface terrain features, ground resistivity measurements, and limited borehole data was used to map the probability of subsurface permafrost, soil type, and soil water content. A surface terrain feature-derived probability of permafrost based on expert opinion (terrain prior) was used to identify the location and type of permafrost that might be present. Also, a probability relationship determined between ground resistivity and permafrost (resistivity prior) was used to predict the variation of probabilities of permafrost. The preliminary probability of permafrost map was used to identify regions of variation in the probability of permafrost, which were used to select locations to drill bore-holes that were then used to provide ground truth and to improve the accuracy of permafrost maps.

Data from borehole core analysis on the presence of ice, soil type, and water content were used to replace the resistivity prior with a resistivity–permafrost probability relationship based on local measurements. Calibrated relationships between resistivity and soil, and resistivity and water content were developed using core data from boreholes; these data were then used to create probability of soil type, water content, and distribution of permafrost (Figure ES-3).

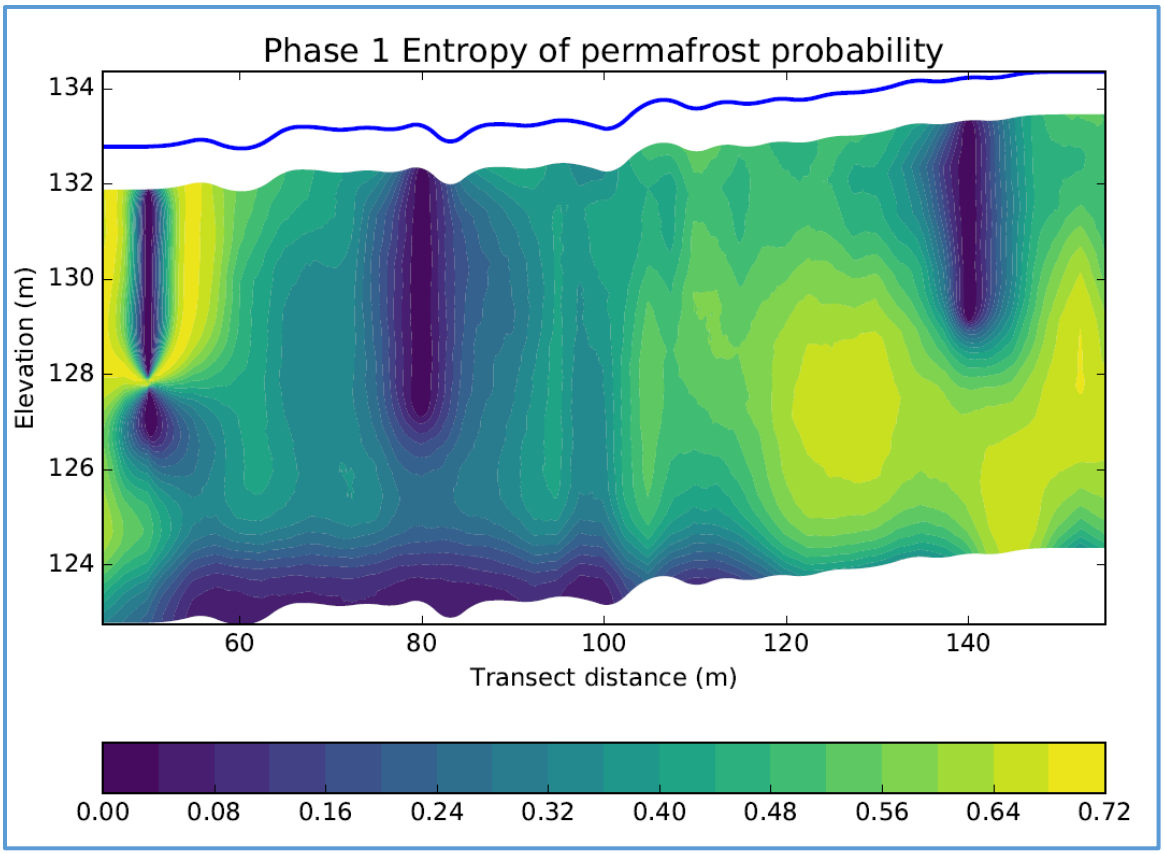

Figure ES-3. Entropy of Predicted Permafrost Using Resistivity and Boreholes at 50m, 80m, and 140m.

Higher values represent greater uncertainty. The areas of low uncertainty surround the locations of the boreholes. Highest uncertainty occurs in the area between observations of permafrost and thawed soils.

The data analysis was conducted using up to eight years of extensive subsurface temperature data that monitored the performance at five structures situated on epigenetic permafrost in Fair-banks, Alaska. These data were analyzed to provide a better understanding of the ground and foundation response in permafrost and to identify any deficiencies in the instrumentation in-stalled on these foundations so that existing instrumentation can be augmented, or to ensure that data are sufficient to answer foundation performance questions. Also, a finite-element thermal modeling was developed to evaluate temperature in complex scenarios, such as beneath structures. This method permitted modeling of various configurations for soil, insulation, and building geometries while accounting for complex considerations of properties such as the latent heat of water, unfrozen water content, varying air temperatures, n-factors (which represent surface conditions), and variability of ground thermal conductivity as a function of temperature. This modeling process allows for more accurate calculations of more complex geometries.

This study also formulated empirically vetted recommendations for an Early Warning Detection System (EWDS) for detecting when permafrost thaw is producing instability that may impact a building's foundation and climate effects. EWDS involves monitoring ground temperatures in critical areas under foundations; however, this temperature information must be considered in the context of how the changing subsurface thermal regime could adversely affect the building structure. This project describes the overall approach used for the EWDS process together with that used for thermal modeling; it leveraged long-term experience at CCHRC to recommend robust, effective approaches and designs for integrated modeling and monitoring.

The ultimate technology for this study is the Permafrost Foundation Decision Support System (PFFDSS). The PFFDSS is a web-based tool that allows engineers to harness the expertise developed through the project team's site characterization, geostatistical analyses, and evaluation of foundations to make better-informed selections of foundation types for vertical and horizontal infrastructure on permafrost landscapes. The tool is intended to be open to all audiences and to benefit multiple users:

- **Engineers New to Permafrost Conditions**. Students and engineers new to design atop permafrost can use the tool to learn about issues unique to building on permafrost, and to better frame and inform their approach to site assessment and foundation design selection.
- **Experienced Engineers**. Experienced engineers will find the data integration capabilities of the PFFDSS useful for quick, efficient, and highly visual assessments of proposed sites.
- **Engineering/Research Offices**. The PFFDSS provides a stable, central location for long-term storage and archival of baseline data for use in further studies and future design work.

A compilation of historical information from Russian literature starting in the 1950s included valuable data on various material physical properties, lessons learned, and protective measures for design of foundation in permafrost areas. For example, the first experimental building de-signed and constructed according to the passive design alternative was a nursing home on permafrost in the Vorkuta region, in Russia, which was built in 1946

with a ventilated crawl space; most buildings since the late 1940s have been constructed with permafrost protection. Information derived from existing literature and expert knowledge were incorporated into the PFFDSS (Figure ES-4) to provide guidance and best practices for selection of foundation type.

The PFFDSS can accept both geophysical transect data and borehole sample data, and integrate and display them on the map and in a vertically-aligned transect chart that depicts transect elevation/topography, spatially explicit resistivity values, interpreted soil type and stability, and potential thaw settlement. A benefit of this approach is that users can aggregate all of their data in a single location and keep track of multiple sites as they evaluate foundation types in the de-sign process.

The geographical information system (GIS) data sources that inform the Desktop Assessment include surficial geologic features and ground ice content. The geologic features layer consists of digitized U.S. Geological Survey (USGS) quad maps covering much of the region around Fairbanks, Alaska. These data were the product of surveys conducted by Péwé (1975).

These data contain a moderate level of detail, but comparable data were unavailable beyond this geo-graphic area. Lack of detailed, reliable data on surficial geology are overwhelmingly the common condition throughout permafrost-affected parts of Alaska. As a result, Desktop Assessments must be undertaken without the benefit of these data in most areas. The ground ice content dataset does cover the entire region, but these are rough estimates at coarse resolution for a parameter that is markedly variable spatially. Also, the ground ice content dataset is highly critical for effective site assessment and is extremely difficult to estimate with accuracy using surface proxies, as this dataset has. These GIS-based ground ice data should therefore only be used as a rough guide within the Desktop Assessment.

The PFFDSS currently facilitates an overall prototype site assessment through the Desktop Assessment, Field Survey, and Foundation Type Assessment phases. Algorithms are integrated for evaluating the Development Difficulty Factor (DDF), stability of soil layers at the site, and potential thaw settlement at the building site if a "reference foundation" is used. The project team's definition of a reference foundation is a slab-on-grade, heated structure. The algorithm for Foundation Type Assessment consists of five foundation types, which are compared against the data from the site that depict permafrost conditions; the respective estimates of cost and risk for each foundation option is also incorporated as part of the algorithm (Figure ES-4). All of these algorithms in the PFFDSS were developed in consultation with the entire project team, which reached a consensus on the outcome from data, analytical methods, and results.

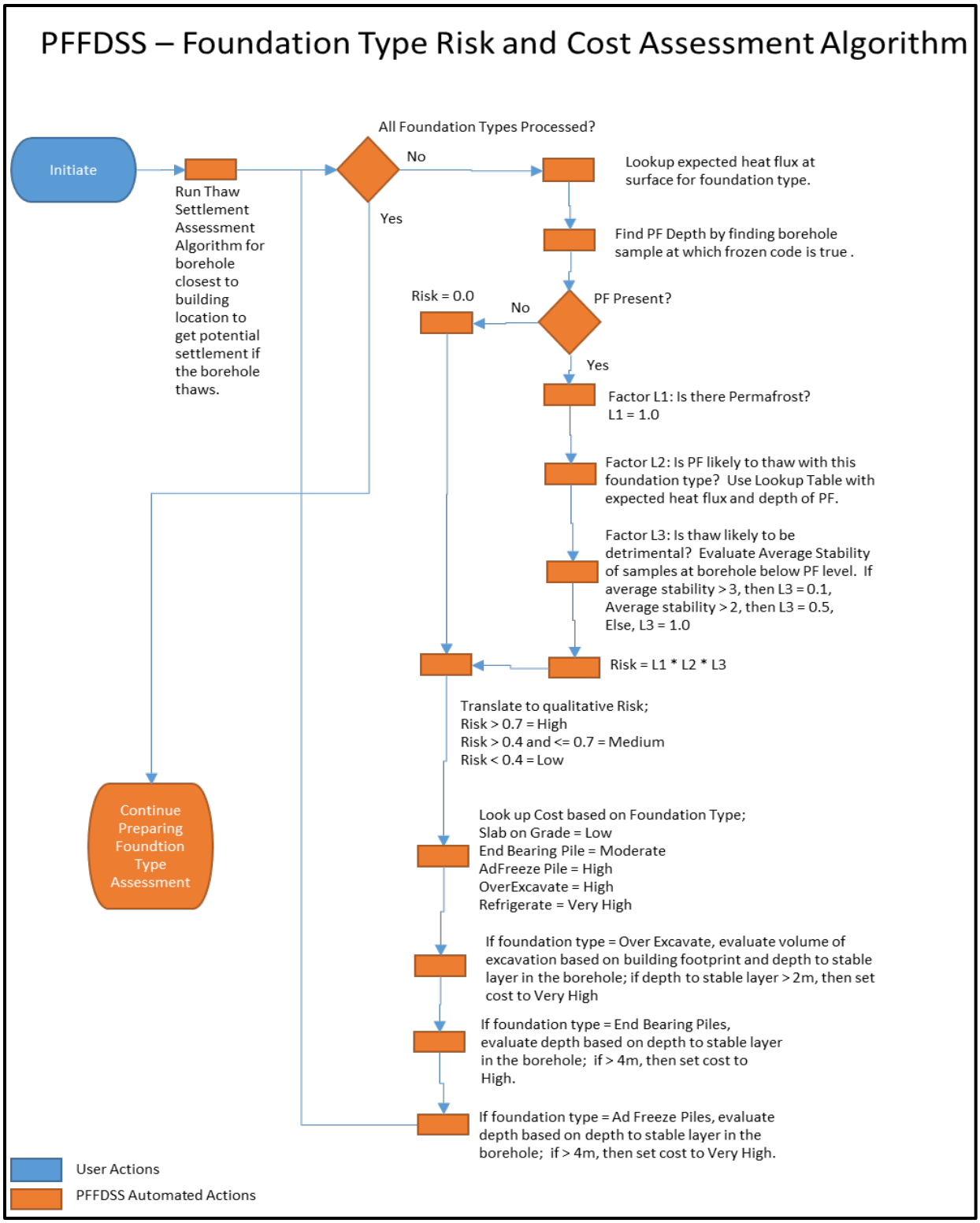

Figure ES-4. PFFDSS Example Flowchart for Foundation Type Risk and Cost Assessment Algorithm.

4.0 RESULTS AND DISCUSSION

4.1 SITE CHARACTERIZATION

The Bayesian geostatistical analysis using surface terrain features, ground resistivity measurements, and limited borehole data was integrated to map the probability of subsurface perma-frost, soil type, and soil water content to characterize potential building sites. Surface terrain feature-derived probability of permafrost based on expert opinion (terrain prior) was applied to identify the location and type of permafrost that might be present. The variation of probabilities of permafrost were determined through an iterative process. The primary permafrost map based on resistivity priors is probably adequate to map where permafrost exists or is not present. Transition regions between permafrost and non-permafrost regions may be missed due to the volume averaging of resistivity from both permafrost and non-permafrost data. The probability of a permafrost map based on three boreholes (approximately 50 m between drill holes) is adequate to predict the spatial variation of permafrost and to identify the transition between permafrost and non-permafrost regions. A fourth borehole (approximately 33 m between boreholes) would significantly improve the resolution of probability of permafrost, soil type, and water content maps. This is demonstrated by the significant improvement in data for soil type and water content from using six boreholes (approximately 25 m between boreholes), as compared to three boreholes, to provide data to the geostatistical analysis. In general, the approach generated rea-sonable probability mapping and profiles of permafrost (Figure ES-3). Given the high probabilities of permafrost and the resolution for soil type and water content probability maps, additional boreholes would likely not provide data to significantly improve probability maps of perma-frost, soil type, and water content.

4.2 FOUNDATION ASSESSMENT

This study reviewed the temperature sensors and data installed in the instrumented CCHRC's Research and Testing Facility (RTF) and neighboring University of Alaska Fairbanks Sustainable Village. The RTF has three distinct foundation types: basement, slab-on-grade, and heated slab-on-grade. Two of four residential homes of the Sustainable Village are built on steel piles that extend 10 m into the ground, while the two western homes were constructed on polyurethane spray foam raft foundations, 254 mm thick, which are directly on the ground. Of the 237 original temperature sensors installed in and around the CCHRC, there are approximately 67 temperature sensors remaining in the original foundation providing useful data. Similarly, most of the sensors under the RTF building were malfunctioning due to sensor failures. Of the instrumentations installed in 2012 to monitor the ground in the four residential homes of the Sustainable Village, only the sensors under the northwest building were functional and most of the temperature sensors under the western houses had ceased to function within a few months after they were installed due to a combination of moisture infiltration and power irregularities. Be-cause these sensors were not accessible and could not be replaced, a new set of sensors and loggers were installed in October 2014 in new holes drilled from outside the houses.

However, available temperature data taken from the ground under the north lab foundation in the RTF indicated that permafrost depth has increased (or degraded) by approximately 1.2 m over the eight years (between 2007 and 2016). Variations of permafrost depth from 1.75 m in 2016 to 5 m in 2013 were observed under the northwest building of the Sustainable Village. On the other hand, the permafrost depth was much shallow (1.2 m in 2016) under the northwest building of the Sustainable Village.

The primary lesson learned from the project team's assessment was that the monitoring of the original RTF and Sustainable Village included insufficient sensor metadata and lacked a clear plan for data analysis; these deficiencies made it difficult to interpret the data. A clear plan should be established before the installation to ensure that sensors are placed in optimal locations and also into the permafrost to ensure that measurements below the permafrost table are taken to reflect any indications of permafrost degradation. Instrumentation and other data system infrastructure should be properly installed in PVC pipe or conduit to increase their long-term durability, and regularly checked by reviewing the data to ensure that the systems are properly functioning. A data management plan should be established to ensure that the data-logging equipment is functioning properly and if necessary, that it is properly adjusted. The plan should include documentation that describes the sensor layout and that includes a regular schedule to review the data for consistency. The instrumentation design should be flexible enough to allow the sensors to be adjusted to accommodate needed measurement changes (e.g., to obtain better resolution in a region where the permafrost has more potential to thaw).

More importantly, thermal modeling could be a useful tool for predicting the permafrost table depth, which is information that can then be used to adjust the locations of the sensors; the data from the sensors can be used to verify the model. Understanding the changes in frozen soil beneath the foundation is crucial to model verification since the integrity of the foundation may depend on soil-bearing capacity and on the assumption that the ground remains frozen.

4.3 EARLY WARNING DETECTION SYSTEM (EWDS)

Guidance for developing an EWDS has been in progress at CCHRC since 2006 when the RTF was originally built. This project has allowed researchers to explore the progress of this development. The development of these early warning detection systems has led to the current system, which puts the temperature data into context to provide useful information to the building manager/engineer. Additionally, a distributed temperature sensor (DTS) was deployed under one of the structures at the Sustainable Village during the winter of 2015–2016 to test its effectiveness in illustrating locations of thermal bridging, and to determine the optimal placement of the EWDS. Note that the DTS was not originally part of the proposal for this project.

Finally, as the EWDS is being developed, it is important to emphasize that the system comprises a process with an end product, the ultimate purpose of which is to adequately detect subsurface thermal conditions that pose a threat to structures. Finite-element thermal modeling should be employed to determine where critical locations exist for EWDS installation.

4.4 PERMAFROST FOUNDATION DECISION SUPPORT SYSTEM (PFFDSS)

The PFFDSS is currently a fully constructed and functioning prototype, in which all three assessment phases are in place and logically linked. The current version of the PFFDSS offers the following:

- A simple step-by-step interface to introduce engineers without permafrost experience to the important factors and considerations in permafrost foundation design.

- A partitioning of the assessment process into desktop and field surveys, which allows the user to refine the list of specific locations within the site, and to focus costly field data collection transects after a walking survey of the site.
- A central location for users to aggregate and integrate their data.
- Assessment algorithms that reflect the consensus of the project team and, as such, that offer a theoretically-sound, technically valid point of embarkation for future development and refinement.
- Innovative methods for presenting results that help users understand their data. (An example is the Swath analysis, which interprets the borehole sample data into a map-based surface of depth to a stable layer in the subsurface and a map-based surface of potential thaw settlement if a reference foundation type [slab-on-grade heated structure] were built there.)

This report describes and illustrates the PFFDSS technological design, including the structure of the interface and the general system architecture; it also includes the user guide and instruc-tions. The current version of the PFFDSS is a fully constructed and functioning prototype, in which all three assessment phases are implemented and logically linked. The project team con-siders the tool to be an affirmative proof-of-concept that provides a solid foundation for contin-ued refinement and expansion. It is the project team's considered opinion that the prototype PFFDSS is not yet suitable for fully vetted site assessments. This is mostly due to the complex nature of the analyses and permafrost conditions at hand, coupled with the pure novelty of the approach. Nevertheless, iterative, long-term testing, refinement, and expansion of the tool that leverages progressive feedback from willing testers and beta-users will yield a reliable, practi-cal utility that will serve a broad user base.

5.0 IMPLICATIONS FOR FUTURE RESEARCH AND BENEFITS

Based on the findings of this project, there is a critical need to do the following:

- *Refine and expand the PFFDSS*. The current version of the PFFDSS is a fully constructed and functioning prototype that implements and logically links all three assessment phases. The tool is currently an affirmative proof-of-concept that accommodates continued refinement and expansion.
- *Further develop the concept of thermal modeling*. Thermal modeling is a complex and useful tool that provides feedback to the foundation designer to better account for the thermal impacts of their structure on frozen ground. Thermal modeling can be used to predict the permafrost table depth and to provide ancillary information to the PFFDSS tool. The scope of this work mainly included a consolidated resource for some-times hard-to-find pertinent thermal modeling parameters used in defining material properties and pertinent boundary conditions in cold climates. Additional guidance for building the thermal model would provide users the skills necessary to understand model output and evaluate the appropriateness of the model results.
- *Generate and compile suitable parameters for finite-element thermal analysis*. This work developed finite-element thermal modeling to evaluate temperature in complex scenarios, such as beneath structures, to permit modeling of various configurations. Further development of this modeling process would allow for more accurate calculations of more complex geometries, e.g., to determine where critical locations exist for EWDS installation.

- *Develop a separate tool to assist engineers or designers to improve the long-term performance of infrastructure under conditions of increased future risk associated with climate change*. This tool would be used to examine the Mean Annual Air Temperature (MAAT) value for predicting temperature projections and providing indicators of potential changes to permafrost conditions.

6.0 LITERATURE CITED

Péwé, T. L. (1975), Quaternary Geology of Alaska. U.S. Geol. Survey Prof. Paper 835, 139 p.Rep.