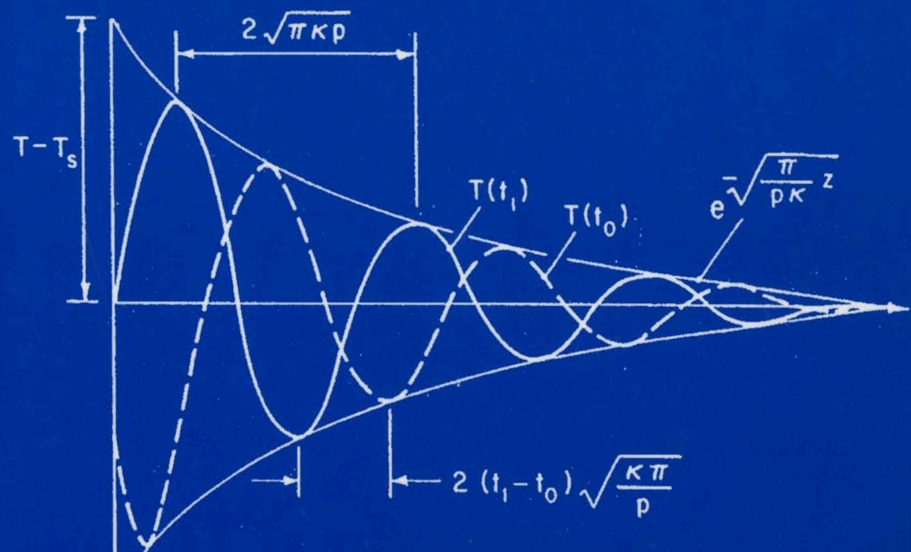
Technical Council on Cold Regions Engineering Monograph

Thermal Analysis, Construction, and Monitoring Methods for Frozen Ground



Edited by David C. Esch

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Thermal Analysis, Construction, and Monitoring Methods for Frozen Ground

SPONSORED BY THE TECHNICAL COUNCIL ON COLD REGIONS ENGINEERING

EDITED BY
David C. Esch

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FOREWORD

The ASCE Technical Council on Cold Regions Engineering (TCCRE) has established the Technical Committee on Frozen Ground for the purpose of encouraging development of new scientific and engineering knowledge of freezing and thawing of soil-water systems and permanently frozen ground, and fostering dissemination of this knowledge. To help accomplish these objectives, TCCRE is publishing a series of Monographs on various cold regions engineering subjects. Each monograph reviews the state of the practice within a defined area through a set of papers written by invited experts in the field.

This Monograph is the ninth in the series and the first of the 21st century. It focuses on the methods used to control freezing and thawing of soils in engineered facilities, on the calculations used to predict the thermal consequences and analyze the benefits of various approaches, and on the field monitoring methods used to monitor thermal performance. Much of it was drawn from an earlier monograph, published by ASCE in 1985, and titled *Thermal Design Considerations in Frozen Ground Engineering*. All of the nine chapters in that volume were incorporated in this new monograph, with most of them being extensively revised and updated. Four new chapters were added to cover recent developments in this field, including an overview of the forecasts and anticipated consequences of climate change on cold regions.

Many people were involved in the preparation of this monograph. The chapter authors are to be given most of the credit and the fact that many are not ASCE members is particularly noted. Thanks are due to the Editors of the previous monograph noted above; R.G. Tart and T.G. Krzewinski. This monograph was edited by D.C. Esch, with the extensive assistance of Susan Mitchell at Inkworks of Fairbanks, who converted the earlier monograph chapters into a uniform format, incorporated updates and review comments, and prepared the final document for publishing. Each paper had at least two technical reviews. In the table that follows all reviewers are listed, and their assistance is greatly appreciated. Without them this monograph would not be of the high quality that it is. All papers (chapters) are eligible for discussion in the *Journal of Cold Regions Engineering* and all papers with significant new content are eligible for ASCE awards.

REVIEWERS

Connor, Billy
Alaska Dept. of Transportation
Fairbanks, AK

Esch, David C.
Alaska Dept. of Transportation
(retired)
Palmer, AK

Hayley, Don W.
EBA Engineering
Edmonton, Alberta

Heuer, Christopher F.
Exxon Production Research
Houston, TX

Johnson, Eric G.
Alaska Dept. of Transportation (retired)
Anchorage, AK

Kinney, Thomas
Hong-West, Inc.
Seattle, WA

Krzewinski, Thomas C.
Golder Associates
Anchorage, AK

Lunardini, Virgil
USA-CRREL (retired)
Hanover, NH

McHattie, Robert
Alaska Dept. of Transportation
(retired)
Fairbanks, AK

Osterkamp, Thomas
University of Alaska
Fairbanks, AK

Pischer, David
Dames & Moore
Anchorage, AK

Ryan, William
CH2M Hill
Medford, OR

Rooney, James
R&M Consultants
Anchorage, AK

Tart, Rupert G.
Golder Associates
Arlington, WA

Thomas, Howard
CH2M Hill
Anchorage, AK

Zarling, John P.
University of Alaska
Fairbanks, AK

Zirjack, Winston
(formerly) Moolin & Assoc.
Anchorage, AK

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INTRODUCTION

Norbert R. Morgenstern, Professor of Civil Engineering, University of Alberta, Edmonton, Canada, and David C. Esch, Monograph Editor

This monograph is first in the twenty-first century in a series on cold regions engineering sponsored by the Technical Council on Cold Regions Engineering of the American Society of Civil Engineers. Many of the chapters were originally contained in the ASCE Technical Council on Cold Regions Engineering monograph titled *Thermal Design Considerations in Frozen Ground Engineering*, edited by T. G. Krzewinski and R. G. Tart, and published in 1985. In the eighteen years that have passed since that time, numerous improvements have been made in thermal design, monitoring and analysis procedures, and construction methods. Therefore, each of the original nine chapters has been reviewed and updated extensively where possible. In addition, five new chapters have been added to provide much more useful information to the engineer working on cold regions problems. This new content has justified the new name now assigned to this monograph: *Thermal Analysis, Construction and Monitoring Methods for Frozen Ground*. It is intended to provide a background on ground heat transfer analysis and discussions and examples of control methods in use during the twentieth century, along with information to guide the reader in the selection and design of construction methods for foundations based on frozen soils. A number of existing textbooks provide a more extensive background in the theory of thermal analysis (for example, Lunardini, 1981). These works appear in the more specialized literature concerned with cold regions and permafrost engineering. The intent of this volume is to provide a basic reference document for civil engineers working or planning to work in cold regions. It also reflects the current state of practice. Ground-temperature studies are only rarely part of engineering curricula, and therefore, the requirements of practice in this regard should be evaluated with the assistance of those specializing in the field. An inadequate understanding of ground-temperature phenomena has resulted in numerous failures and costly repairs to engineering protects in cold regions. The presence of flowing subsurface water can alter the thermal behavior in unpredictable ways, and this factor is always site specific and difficult to analyze.

All aspects of cold regions civil engineering must be sensitive to heat transfer effects, whether it is designing a building envelope, designing a foundation on permafrost, burying utilities, or estimating construction costs (making allowance for reduced productivity due to cold). However, ground-temperature phenomena impact primarily on geotechnical engineering considerations, where the objective is to evaluate the pre-existing geothermal regime and either preserve it or modify it on-site, with due cognizance of the engineering and environmental implications of changes in the ground thermal regime.

In North America, modern ground-temperature studies in cold regions have three antecedents. One resides in the efforts made in the 1950s and 1960s to produce simplified methods for calculating the depth of freeze and thaw in soils, with primary emphasis on the design of roads and runways. The second resides in the efforts of geophysicists to comprehend the geothermal regime in polar regions, which also resulted in many contributions of practical interest. The final impetus for expanded research on the subject came from the intensive research in the 1970s for the development of analysis methods to predict the effects of permafrost and frost heave on the Trans-Alaska oil pipeline.

The classical studies of Kersten (1949) on the thermal properties of soils and those by Aldrich and Paynter (1953) on analytical studies of freezing and thawing of soils have stood the test of time and remained standard and valuable references. These and related studies were synthesized in *U.S. Army Technical Manual* TM 5-852-6 (1966), dealing with calculation methods for the determination of depths of freeze and thaw in soils. Over this same period, Arthur Lachenbruch diverted his interest from the geothermal regime of polar regions to several problems of practical interest related to heat conduction in permafrost and prepared several technical papers on the subject (Lachenbruch, 1957, 1959, 1972). Therefore, the practicing engineer of three decades ago had reasonable access to information about soil thermal properties. Also, variety of one-dimensional and some multidimensional solutions to ground heat conduction problems had been simplified to facilitate their use in practice. The development of the personal computer in the 1970s and 1980s led to the development of thermal modeling programs that greatly increased the speed of analysis and allowed more precise predictions if used with appropriate soil properties.

When ground temperatures are controlled by heat flow at the air-ground interface, it is necessary to determine the temperature conditions at the ground surface in order to perform thermal calculations. The combined effects of radiative, convective and conductive heat exchange at the air-ground interface control the surface temperatures. Heat and mass transfer phenomena at this interface are complex and data are rarely available to evaluate the energy balance at this interface in order to estimate the ground heat flux. Since air temperatures are generally available and surface temperatures are not, a correlation between these temperatures is required to establish the thermal boundary condition at the ground surface. This problem resulted in the "n-factor" approach, which correlates ground surface temperatures to the air temperatures. Tables of n-factors, which are the ratios of surface-to-air freezing and thawing indices, were also developed starting in the 1950s and were found adequate for many design purposes (Lunardini, 1978). The state-of-practice for ground-temperature studies in cold regions in the mid-1960s was essentially that synthesized in the design manuals of the U.S. Army and the Air Force (1966).

By the end of the 1960s the oil and gas industries took over as the engine of growth in the cold regions of North America, and a dramatic expansion occurred in the need to observe the ground-temperature regime in cold regions in order to understand the factors that influence it and to undertake designs to either maintain the thermal regime or modify it in a controlled manner. The forecasted impact of burial of a proposed hot oil pipeline in ice-rich permafrost remains a vivid reminder of the early part of this phase of cold-regions engineering (Lachenbruch, 1970).

Driven by the need to solve important geothermal problems and armed with new monitoring instruments, heat transfer devices, and computational tools, progress through the 1970s and '80s has been rapid. The scope for comprehensive geothermal investigations has increased. The chapters that follow illustrate this practice.

CHAPTER OVERVIEWS

Chapter 1 provides an overview of ground-temperature observation practices. Just as the geotechnical engineer is sensitive to the influence of minor geological details that can control subsequent performance, so is the geothermal engineer sensitive to the influence of minor environmental details that can dominate the local ground-temperature distribution. The type, density, and properties of vegetation, and the amount, timing and properties of the snow cover will greatly influence the depth of the active layer, and will, in fact, determine the presence or absence of permafrost in many regions. Flowing water can also have a substantial effect on ground temperatures. Gold and Lachenbruch (1973) discuss in detail the boundary conditions affecting the distribution of permafrost. Examples of ground thermal regime from borehole temperature measurements at variety of locations are given in Chapter 1.

Because of the accumulating evidence that global climatic warming is occurring, and that this warming may be most intense in the Arctic and sub-Arctic regions, projected future climatic factors should be seriously considered for certain temperature-critical geothermal designs. For example, the design of critical pilings supported by adfreeze bonding between frozen soils and pile surfaces must rely on consistent long-term soil temperatures, or use conservative estimates of future temperature change scenarios. The current evidence for global climate change and the use of prediction models for future climate forecasts are discussed in Chapter 2, prepared by Dr. Gunter Weller, a noted Alaska expert on global change literature and on current studies in this interesting and critical area.

Ground-temperature measurements are now made routinely in most arctic engineering projects. Techniques for conducting these measurements are summarized in Chapter 3. The most commonly used sensors for ground-temperature measurements in North America are the thermocouple and the thermistor. Of these, the thermocouple is the most stable and economical but the most difficult to read accurately under field conditions. The thermistor provides the most precision and allows economical temperature readings to an accuracy of 0.1° C. However, their long-term stability problems must be considered. Guidance on installation and observational practice is given in this chapter. The development of low-cost, battery-powered field data loggers is a recent development that provides the potential for obtaining almost unlimited field data on surface and subsurface temperatures.

Chapter 4 contains a comprehensive summary of the use of passive techniques for ground-temperature control. The term "passive technique" refers to any method that requires no external power during operation and has no moving mechanical parts. In many instances, cold regions foundation problems are resolved by maintaining the frozen state of the ground and by controlling the ground thermal regime within acceptable limits. Both passive and active techniques can be employed to modify ground temperatures before construction and for controlling it afterwards.