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Thermal modeling of roadway embankments over permafrost

Margaret M. Darrow *

University of Alaska Fairbanks, Fairbanks, AK, United States

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ABSTRACT

Thermal degradation of permafrost beneath embankments is an on-going problem in highway design. In recent years, engineers with the Alaska Department of Transportation and Public Facilities have used a commercially available, two-dimensional finite element model to determine the embankment's effect on the thermal regime of the foundation soils; however, the modeling was done with historic air temperature data and input parameters derived from the literature, rather than site-specific data. Temperatures and soil properties were measured at two different research sites in Alaska to compare against model results. A sensitivity analysis of certain input parameters was conducted on the model for each site. Analysis of the model results indicates that the most critical input parameter is the surface boundary condition, which is separated into air temperature and modifying *n*-factors. Using site-specific air temperature data resulted in models that closely matched the measured soil temperatures, and either matched or overestimated the active layer depths. If used for design purposes, the thermal modeling would result in a more conservative embankment construction, which is favorable if a warming climate is considered.

1. Introduction

Areas of Alaska's highways experience distress due to the thawing of ice-rich permafrost below the highway embankments. For the past few decades, Alaska Department of Transportation and Public Facilities (AK DOT&PF) engineers have used a one-dimensional (1-D) thermal modeling program to analyze different embankment heights, both with and without layers of insulation, in order to determine the effects on the thermal regime of the foundation soils. The author, while employed with AK DOT&PF, began to use TEMP/W in 2006, which is a commercially available two-dimensional (2-D) finite element program. Because this model incorporates 2-D boundary effects, it is more accurate than a 1-D model.

For a typical analysis using TEMP/W, the author finds historical air temperature data as close to the project site as possible; in many cases, the nearest collection point is more than 50 miles from the project site and/or more than 30 years out-of-date. The model input parameters for soil (e.g., frozen and unfrozen thermal conductivity, and dry unit weight/volumetric water content) and surface boundary condition modifiers (i.e., *n*-factors) are selected from widely recommended charts and tables of representative values available in the literature. In other words, these input parameters are "educated guesses." The modeling results of such an analysis suggest a typical temperature configuration within/and below the embankment and at the embankment toe, which is grossly consistent with visual observations of embankment performance, as well as with

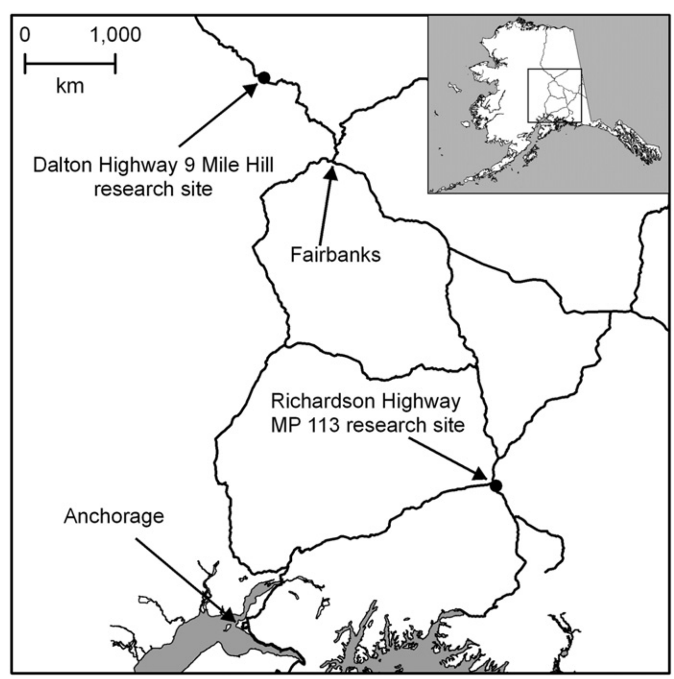

Fig. 1. Location of the two research sites, relative to the major highways in Alaska and to Fairbanks and Anchorage.

* Tel.: +1 907 474 7303; fax: +1 907 474 6635.
E-mail address: margaret.darrow@alaska.edu.

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the measured thaw depth progression at certain locations (Esch, 1994). These modeling results, however, are not checked for accuracy against actual field conditions. Gosink et al. (1986), in their testing of two computer models for the ground thermal regime, indicated that "…a complete data set including the thermal and hydrological regimes and measurements of all model parameters is urgently required to test numerical models of heat and mass transport." These authors recommended that a research program be initiated to measure these needed input parameters, specifically thermal and hydrological parameters such as thermal conductivity and unfrozen water content.

Smith and Riseborough (2010) modeled the effects of vegetation disturbance and various climate change scenarios on the permafrost below the right-of-way of the Norman Wells pipeline in northwestern Canada. While these authors compared their results to measured ground temperatures, the modeling did not incorporate thermal effects from the pipeline or construction activities. Liu and Tian (2002) conducted 2-D modeling of a variety of embankment designs with and without insulation, placed over soils and permafrost conditions typical of the Fenghuoshang region of Tibet. Their study was limited to computer simulations. A comparison of thermal modeling results and measured temperatures was conducted for an experimental buried chilled gas pipeline located in discontinuous permafrost outside of Fairbanks, Alaska (Darrow, 2009); however, to the best of the author's knowledge, a similar analysis has not yet been conducted for thermal models of embankments over permafrost.

This paper presents the results of a research project having the overall goal to compare modeling results to field data. To achieve this goal, the author: 1) measured temperatures from within existing embankments and the underlying foundation soils at two different locations in Alaska underlain by permafrost with differing climates and soils; 2) measured the thermal and hydrological properties of the soils from these locations; and 3) conducted a "sensitivity analysis" (a term adapted from Grant et al., 1990) of certain input parameters to determine which of these parameters has the most impact on the model results and therefore should be site-specific. Finally, the models were evaluated to determine how well the modeled active layer depth

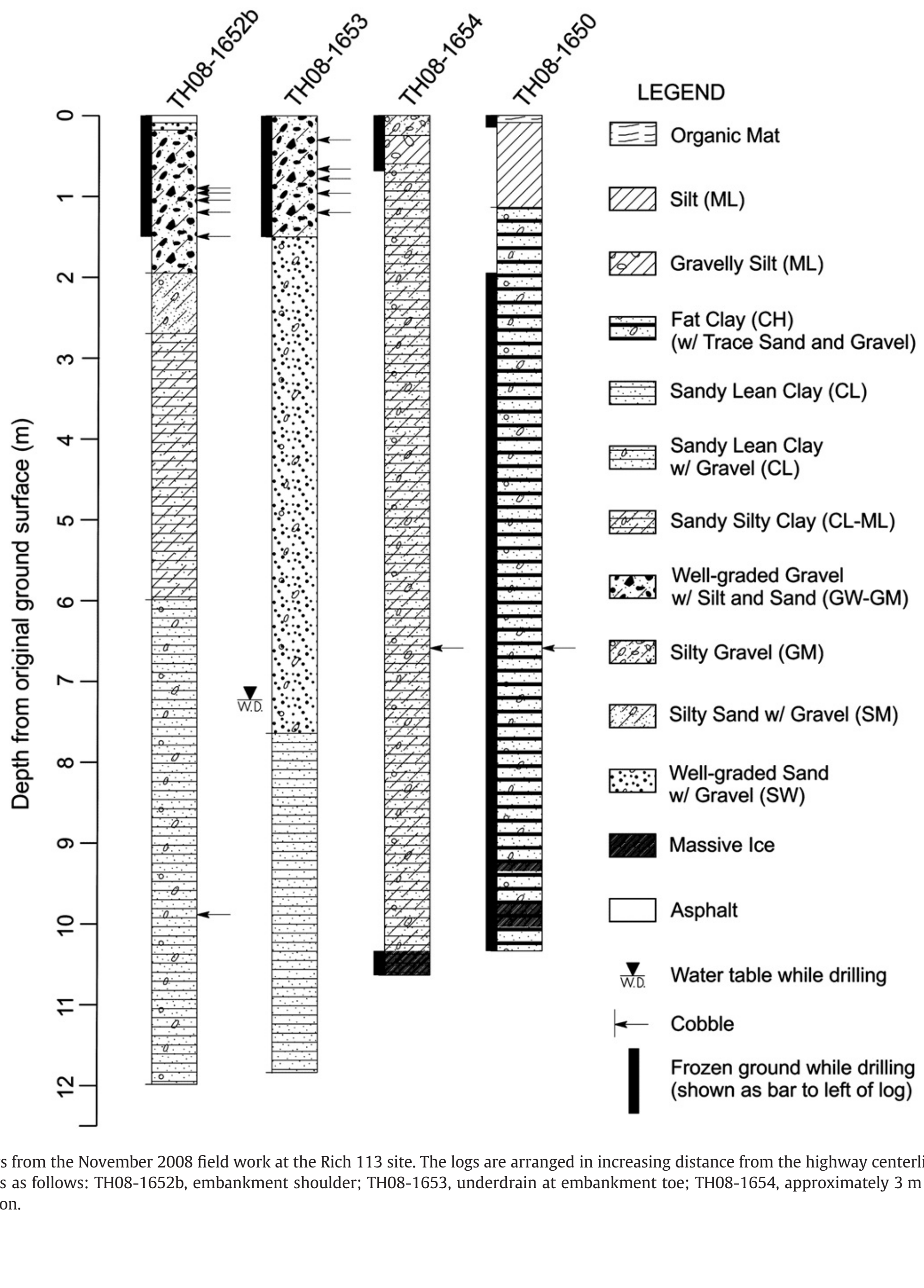

Fig. 2. Test hole (TH) logs from the November 2008 field work at the Rich 113 site. The logs are arranged in increasing distance from the highway centerline from left to right. The location of each boring is as follows: TH08-1652b, embankment shoulder; TH08-1653, underdrain at embankment toe; TH08-1654, approximately 3 m from TH08-1653; TH08-1650, undisturbed location.