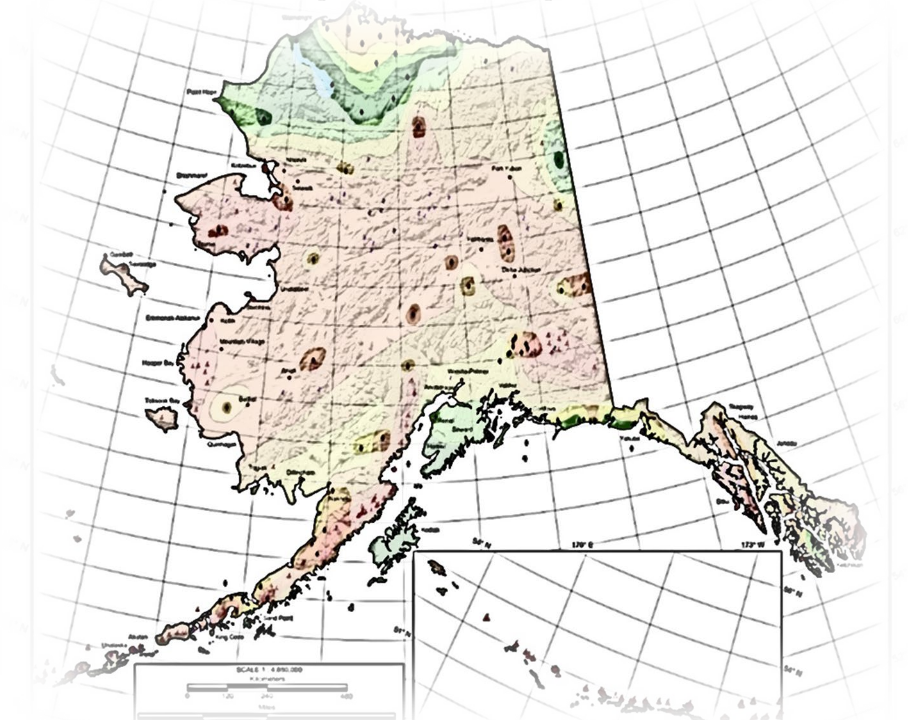
Alaska Department of Transportation & Public Facilities
Research & Technology Transfer

Geotechnical Asset Management (GAM) Through Thermal Modeling and Post-Construction Thermal Monitoring of Highway Embankments for the Dalton Highway MP 0-9 Project

Prepared by: Steve McGroarty, P.E.; Matthew Billing, P.E
Alaska Department of Transportation & Public Facilities



Heat Flow Map of Alaska

Date: August 2019

Prepared for:
Alaska Department of Transportation & Public Facilities
Statewide Research Office
3132 Channel Drive
Juneau, AK 99801-7898

Publication Number: 4000-138

REPORT DOCUMENTATION PAGE

Form approved OMB No.

1. AGENCY USE ONLY (LEAVE BLANK) 4000-138	2. REPORT DATE August 2019	3. REPORT TYPE AND DATES COVERED Final, 2019

4. TITLE AND SUBTITLE

Geotechnical Asset Management (GAM) Through Thermal Modeling and Post-Construction Thermal Monitoring of Highway Embankments for the Dalton Highway MP 0-9 Project

5. FUNDING NUMBERS

Federal #: 4000-138

IRIS #: Z64230000

6. AUTHOR(S)

McGroarty, Steve P.E.; Billing, Matthew P.E.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Alaska Department of Transportation & Public Facilities, Northern Region Materials Section

8. PERFORMING ORGANIZATION REPORT NUMBER

4000-138

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

State of Alaska, Alaska Dept. of Transportation and Public Facilities
Research and Technology Transfer
3132 Channel Drive
Juneau, AK 99801-7898

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

4000-138

11. SUPPLENMENTARY NOTES

12a. DISTRIBUTION / AVAILABILITY STATEMENT

No restrictions

12b. DISTRIBUTION CODE

UNL

13. ABSTRACT (Maximum 200 words)

The thermal model developed for the pre-embankment conditions corresponded well with measured ground temperatures and measured thaw depth.

There was little difference in thaw depth measured between undisturbed areas and locations of winter-only equipment travel. There was a doubling of the thaw depth between undisturbed areas and the locations of summer equipment travel / drilling operations.

Observation of near-surface ground water conditions in test pits provided a mechanism for understanding the observed bi-annual "flat-lining" of near-surface ground temperatures.

Measurement of near-surface ground temperatures allowed for calculation of seasonal n factors for tundra ground cover.

There was good agreement between soil material thermal properties estimated by the methods found in A Generalized Thermal Conductivity Model for Soils and Construction Materials – Côté & Konrad (2005) and traditional estimation methods used by Kersten and Johansen.

Measured soil temperature at various depths allowed for the thermal model to be calibrated by adjusting the soil material thermal properties until modeled cumulative thawing and freezing degree-days matched the measured cumulative thawing and freezing degree-days at depth.

The research program and associated literature review has resulted in changes and refinements to DOT&PF's thermal modeling procedures.

14- KEYWORDS :

GAM, Geotechnical Asset Management, Embankments, Thermal Conductivity, thermal Monitoring

15. NUMBER OF PAGES

82

16. PRICE CODE

N/A

17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT N/A

NSN 7540-01-280-5500

STANDARD FORM 298 (Rev. 2-98)
Prescribed by ANSI Std. 239-18 298-102

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
AREA				
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m^3				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact degrees)				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
ILLUMINATION				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
AREA				
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
VOLUME				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
MASS				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
TEMPERATURE (exact degrees)				
°C	Celsius	1.8C+32	Fahrenheit	°F
ILLUMINATION				
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
FORCE and PRESSURE or STRESS				
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

Geotechnical Asset Management (GAM) Through Thermal Modeling and Post-Construction Thermal Monitoring of Highway Embankments for the Dalton Highway MP 0-9 Project

Final Report

Alaska Department of Transportation & Public Facilities

Northern Region Materials Section

Steve McGroarty, P.E.
Northern Region Geotechnical Engineer

and

Matthew Billings, P.E.
Northern Region Assistant Geotechnical Engineer

August 12, 2019

Table of Contents

List of Figures

List of Tables

Executive Summary:

Research:

- Air and ground temperature data was collected over a two-year period and used to calibrate a thermal model.
- Test pits were dug to characterize vegetation, near-surface soils and near-surface water conditions.
- Thermal model was used to estimate thermal impacts of various road embankment configurations.

Key results and conclusions:

- The thermal model developed for the pre-embankment conditions corresponded well with measured ground temperatures and measured thaw depth.
- There was little difference in thaw depth measured between undisturbed areas and locations of winter-only equipment travel. There was a doubling of the thaw depth between undisturbed areas and the locations of summer equipment travel / drilling operations.
- Observation of near-surface ground water conditions in test pits provided a mechanism for understanding the observed bi-annual "flat-lining" of near-surface ground temperatures.
- Measurement of near-surface ground temperatures allowed for calculation of seasonal n-factors for tundra ground cover.
- There was good agreement between soil material thermal properties estimated by the methods found in A Generalized Thermal Conductivity Model for Soils and Construction Materials – Côté & Konrad (2005) and traditional estimation methods used by Kersten and Johansen.
- Measured soil temperature at various depths allowed for the thermal model to be calibrated by adjusting the soil material thermal properties until modeled cumulative thawing and freezing degree-days matched the measured cumulative thawing and freezing degree-days at depth.
- The research program and associated literature review has resulted in changes and refinements to DOT&PF's thermal modeling procedures.

Recommendations for future research include:

- If the Dalton Highway MP 0-9 Project is constructed, we recommend measuring ground temperatures under the constructed embankment to allow for evaluation of assumed compression of the vegetative mat and near-surface soil layers and changes to their original thermal properties.

- Collaboration with Dr. Doug Goering of the Alaska University Transportation Center, University of Alaska Fairbanks on the Improved Permafrost Protection Using Air Convection and Ventilated Shoulder Cooling System research program.

- Obtain a needle-probe for measurement of soil thermal conductivity and develop practice and procedures for incorporation of this testing into geotechnical investigations. Organic soils from test pits and boreholes should be brought back to NRMS for determination of frozen and unfrozen thermal conductivity at varying moisture contents for the development of a database.

- Collaboration with Dr. Margaret Darrow of the University of Alaska Fairbanks on the measurement of unfrozen moisture content of frozen soil samples obtained from geotechnical investigations and the development of a database of unfrozen moisture content for Alaskan soils.

Research Group:

DOT&PF Project Champion(s):

- Steve McGroarty, P.E., Alaska DOT&PF, Northern Region Geotechnical Engineer

DOT&PF Project Sponsor(s):

- Jeff Currey, P.E., Alaska DOT&PF, Northern Region Materials Engineer

Technical Advisory Committee:

- Jeff Currey, P.E., Alaska DOT&PF, Northern Region Materials Engineer
- Kevin Maxwell, Alaska DOT&PF, Engineering Geologist
- Barry Benko, Alaska DOT&PF, Statewide Materials Section, Chief Engineering Geologist
- Dr. Margaret Darrow, P.E., Professor, Geological Engineering, University of Alaska Fairbanks

Problem Statement & Background:

Geotechnical Asset Management (GAM) involves geotechnical features that can affect the performance of a transportation system and includes the design and construction of road embankments to achieve lowest possible life-cycle asset costs. Road embankments constructed on ice-rich permafrost must promote a thermally stable subgrade in order to minimize thaw settlement and related long-term road maintenance costs.

The Dalton Highway MP 0-9 Reconstruction Project is planned to realign and reconstruct the first nine miles of the Dalton Highway. The first six miles are a new road alignment over foundation soils that include sections of very ice-rich silt and peat and also massive ice. Long-term performance of the realignment will be dependent upon design and construction of an embankment that maintains permafrost in the foundation soils.

Alaska DOT&PF Northern Region Materials Section (NRMS) staff has used GeoStudio TEMP/W, a commercially available two-dimensional finite element computer software program, to construct thermal models of conventional and insulated embankments in an effort to design road embankments that reduce the thawing of ice-rich permafrost in the road subgrade. Past studies using TEMP/W have determined that the most critical model parameter is the surface boundary condition, i.e. the soil surface temperatures. Typically, site-specific soil surface temperatures are not available and are estimated using air temperature records and a modifying n-factor. Material type, vegetation cover, and snow cover can all affect n-factors.

Preliminary thermal modeling using TEMP/W and projected Year 2050-air temperatures indicated that a conventional road embankment incorporating 6-inches of insulation board was not expected to maintain the permafrost in the ice-rich foundation soils and would result in excessive settlement of the road surface. It was considered likely that an Air Convection Embankment (ACE) would be constructed over the ice-rich sections of the alignment. Thermal modeling of an ACE embankment requires the use of AIR/W in conjunction with TEMP/W.

The work plan for Phase I of the research included:

- Installing air temperature monitoring stations for comparing local air temperatures to air temperatures at regional long-term monitoring stations. Adjusting the regional long-term historic temperature record to better reflect site specific temperatures for thermal model input.

- Installing BeadedStream Digital Temperature Cables (DTCs) and data loggers to monitor air vs. soil-surface temperatures for determination of site specific *n*-factors of a spruce forest with tundra for thermal model input.

- Measuring ground temperatures at depth for refinement of model material thermal properties and *n*-factors through an iterative process of adjusting parameters until the modeled active layer thickness and ground temperatures reasonably match measured values.

- Once the thermal model was adjusted such that predicted active layer thickness and ground temperatures at depth reasonably match measured values, the model would be used to evaluate the thermal impacts of various road embankment designs on foundation soils and predict post-construction foundation soil temperatures and thaw-settlement. This would end Phase I of the research program.

Phase II of the research program was planned to include:

- Installing DTCs below and within a newly constructed road embankment, collecting three-years of post-construction ground temperatures, comparing measured to modeled ground temperatures, and evaluating Alaska DOT&PF NRMS Thermal Modeling Methodology. It was assumed the instrumented road embankment would include sections of ACE embankment, which would allow calibration and confirmation of TEMP/W + AIR/W Thermal Models and allow evaluation of the Alaska DOT&PF Air Convecting Embankment (ACE) Design Guide (Hattie & Goering, 2009).

- Since the inception of this research program four separate events have occurred, which cumulatively may negate the original need for Phase II. There are currently three experimental features underway for highway construction projects and a recently approved research program by the University of Alaska – Fairbanks.
    - The three experimental features are: Construction of an Air-Convection Embankment (ACE) With non-Angular ACE Fill (Alaska Highway MP 1354-1364 Rehabilitation Project); Construction of Road Embankments with Reduced Air Convection Embankment (ACE) Shoulder Top-Widths (Dalton Highway MP 209-222 Reconstruction Project); and, Construction of an Air Convection Embankment (ACE) and ACE Shoulders with 1”-2” Rounded ACE Fill (Elliott Highway MP 0-12 Rehabilitation Project).
    - The research project is Improved Permafrost Protection using Air Convection and Ventilated Shoulder Cooling Systems (Dr. Doug Goering). The research program will analyze the data collected from the three highway construction experimental feature projects and the data from a previous experimental feature that included an ACE embankment constructed on Thompson Drive in Fairbanks and develop a TEMP/W + AIR/W modeling methodology.

The construction of the Dalton Highway MP 0-9 Project has been delayed until 2021 or later. We recommend Phase II of Geotechnical Asset Management (GAM) Through Thermal Modeling and Post-Construction Thermal Monitoring of Highway Embankments for the Dalton Highway MP 0-9 be suspended and the need for it be re-assessed once embankment design of the project is completed and the results of the experimental features and research project are evaluated.

Field Investigations

The Dalton MP 0-9 Realignment Project included multiple geotechnical drilling programs in 2014 and subsequent years. Based on the drilling results, two boreholes were selected for long-term ground temperature monitoring; TH14-021 and TH14-103. A revision to the planned route prompted transfer of the ground temperature DTC from TH14-103 to TH15-2053. Figure 1 illustrates the approximate locations of the monitoring stations.

Monitoring Station # 1: BeadedStream Permanent Site # 1 – TH14-021

Monitoring Station # 1 was established at borehole TH14-021. Test hole TH14-021 was drilled on February 27, 2014 and encountered 1 foot of organic mat, 24 feet of ice-rich silt, 9 feet of sand with silt and gravel, and 4 feet of gravel with silt and sand. Subsurface conditions encountered while drilling are shown on the Final Test Hole Log for TH14-021 in Figure 2. Foundation soils were frozen to the depth explored.

The NRMS installed a temporary DTC in TH14-021 in April 2014. Ground temperatures were monitored at this site during the initial geotechnical drilling program between April 7, 2014 and May 20, 2014. The permanent DTC was installed in TH14-021 and has collected ground temperature measurements since December 3, 2014. Air, near-surface ground, ground temperatures extending roughly to a depth of 39.3 feet below ground surface (bgs), and snow depths have been recorded every 6-hours at the site since December 3, 2014. A single-point DTC in a radiation shield was installed to monitor air temperatures. A multi-sensor 1-foot rigid DTC was installed to monitor soil-surface temperatures. A 114-foot multi-sensor DTC was installed in TH14-021 to monitor ground temperatures at 0.3, 1.3, 2.3, 3.3, 4.3, 5.3, 7.3, 9.3, 11.3, 13.3, 15.3, 17.3, 19.3, 23.3, 27.3, 31.3, 35.3, and 39.3 feet below ground surface and soil-surface temperatures at 16 locations (at 4-foot intervals) between TH14-021 and the data-logger location. The DTC was installed in a flexible conduit between TH14-021 and the data logger and the conduit was placed on the surface of the tundra. This horizontal portion of the DTC was buried at the approximate mid-point of the tundra mat (generally 6 inches below the mat surface) on July 6, 2015. Snow depth and air and ground temperature monitoring has occurred since October 23, 2014. A typical pre-construction Monitoring Station is shown in Figures 3 and 4.

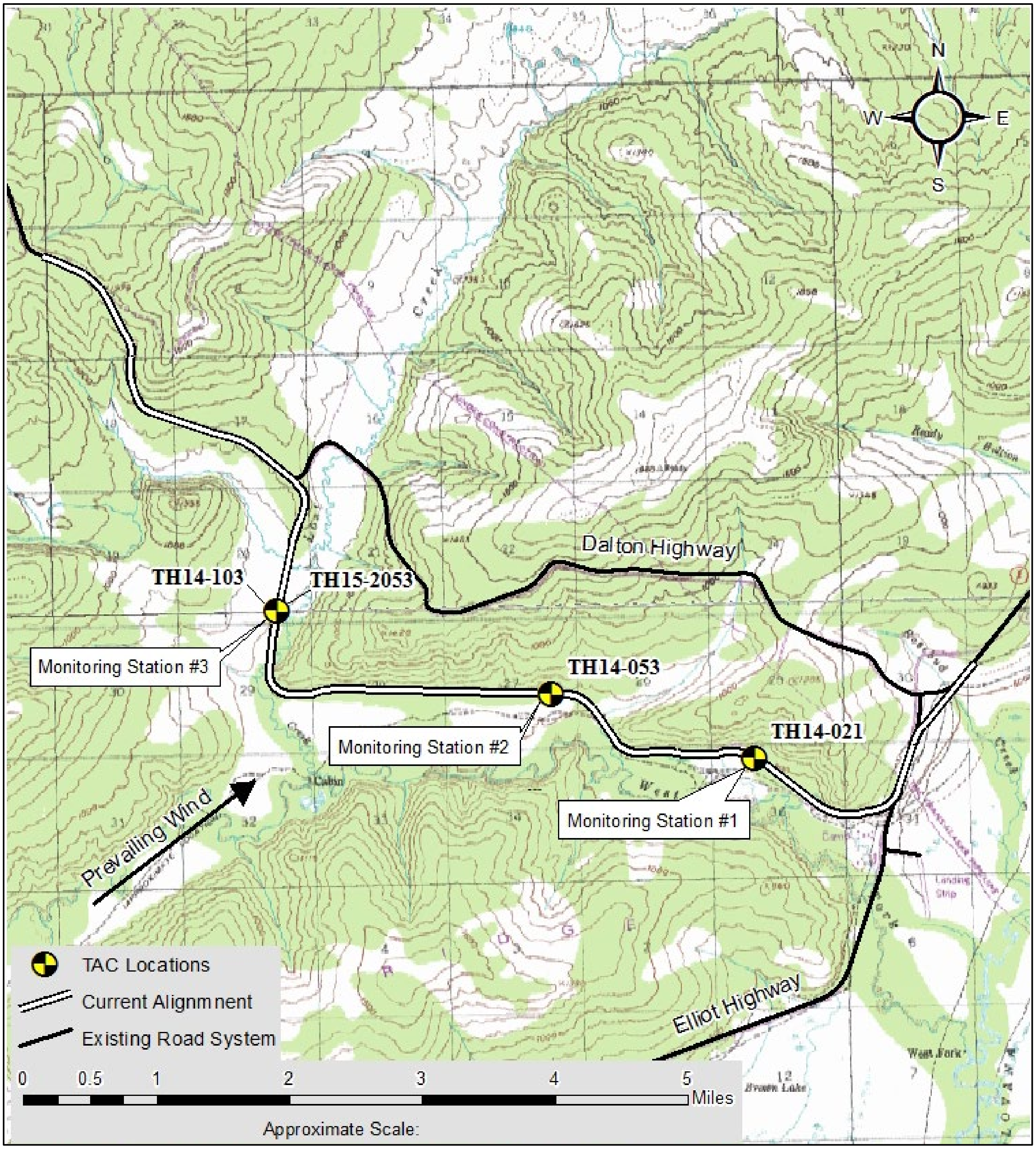
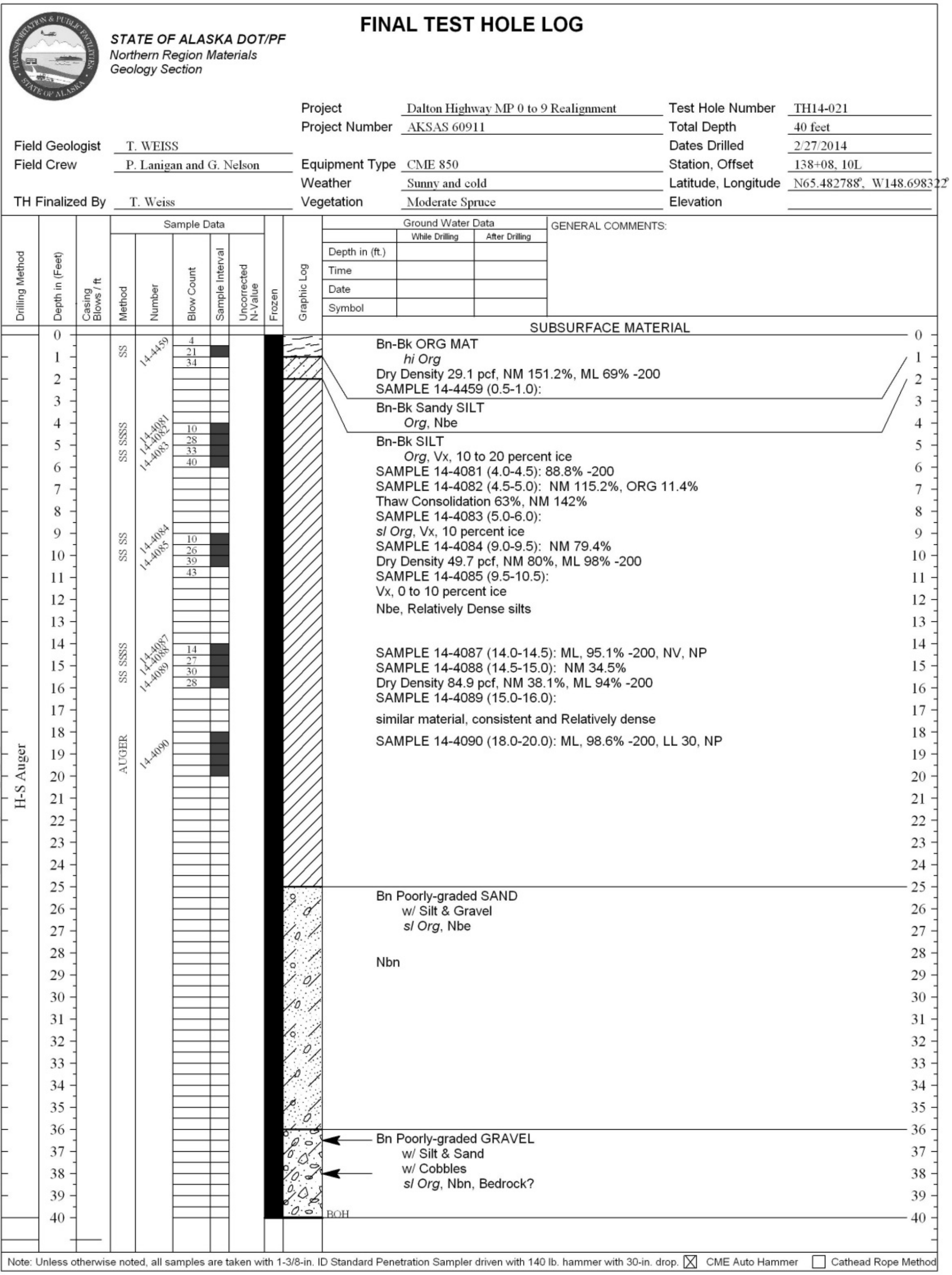


Figure 1. Monitoring station locations. (Note -"current alignment" is "proposed alignment".)



FINAL TEST HOLE LOG

STATE OF ALASKA DOT/PF
Northern Region Materials
Geology Section

Project: Dalton Highway MP 0 to 9 Realignment
Project Number: AKSAS 60911
Test Hole Number: TH14-021
Total Depth: 40 feet
Dates Drilled: 2/27/2014
Field Geologist: T. WEISS
Field Crew: P. Lanigan and G. Nelson
Equipment Type: CME 850
Station, Offset: 138+08, 10L
Weather: Sunny and cold
Latitude, Longitude: N65.482788°, W148.698322°
TH Finalized By: T. Weiss
Vegetation: Moderate Spruce
Elevation:

Ground Water Data	While Drilling	After Drilling
Depth in (ft.)		
Time		
Date		
Symbol		

GENERAL COMMENTS:

Drilling Method: H-S Auger

Depth in (Feet)	Method	Number	Blow Count
0	SS	14-4459	4 21 34
4	SS SSSS	14-4081 14-4082 14-4083	10 28 33 40
9	SS SS	14-4084 14-4085	10 26 39 43
14	SS SSSS	14-4087 14-4088 14-4089	14 27 30 28
18	AUGER	14-4090	

SUBSURFACE MATERIAL

0 – 1: Bn-Bk ORG MAT
hi Org
Dry Density 29.1 pcf, NM 151.2%, ML 69% -200
SAMPLE 14-4459 (0.5-1.0):

1 – 2: Bn-Bk Sandy SILT
Org, Nbe

2 – 25: Bn-Bk SILT
Org, Vx, 10 to 20 percent ice
SAMPLE 14-4081 (4.0-4.5): 88.8% -200
SAMPLE 14-4082 (4.5-5.0): NM 115.2%, ORG 11.4%
Thaw Consolidation 63%, NM 142%
SAMPLE 14-4083 (5.0-6.0):
sl Org, Vx, 10 percent ice
SAMPLE 14-4084 (9.0-9.5): NM 79.4%
Dry Density 49.7 pcf, NM 80%, ML 98% -200
SAMPLE 14-4085 (9.5-10.5):
Vx, 0 to 10 percent ice
Nbe, Relatively Dense silts

SAMPLE 14-4087 (14.0-14.5): ML, 95.1% -200, NV, NP
SAMPLE 14-4088 (14.5-15.0): NM 34.5%
Dry Density 84.9 pcf, NM 38.1%, ML 94% -200
SAMPLE 14-4089 (15.0-16.0):
similar material, consistent and Relatively dense
SAMPLE 14-4090 (18.0-20.0): ML, 98.6% -200, LL 30, NP

25 – 36: Bn Poorly-graded SAND
w/ Silt & Gravel
sl Org, Nbe

Nbn

36 – 40: Bn Poorly-graded GRAVEL
w/ Silt & Sand
w/ Cobbles
sl Org, Nbn, Bedrock?

BOH

Note: Unless otherwise noted, all samples are taken with 1-3/8-in. ID Standard Penetration Sampler driven with 140 lb. hammer with 30-in. drop. ☒ CME Auto Hammer ☐ Cathead Rope Method

NR AKDOT TEST HOLE LOG - USCS TEST HOLE LOGS, FINAL.GPJ NR_AKDOT_PRECON_USCS_06_28_07.GDT 2/11/15

Figure 2. TH14-021 Drill log.

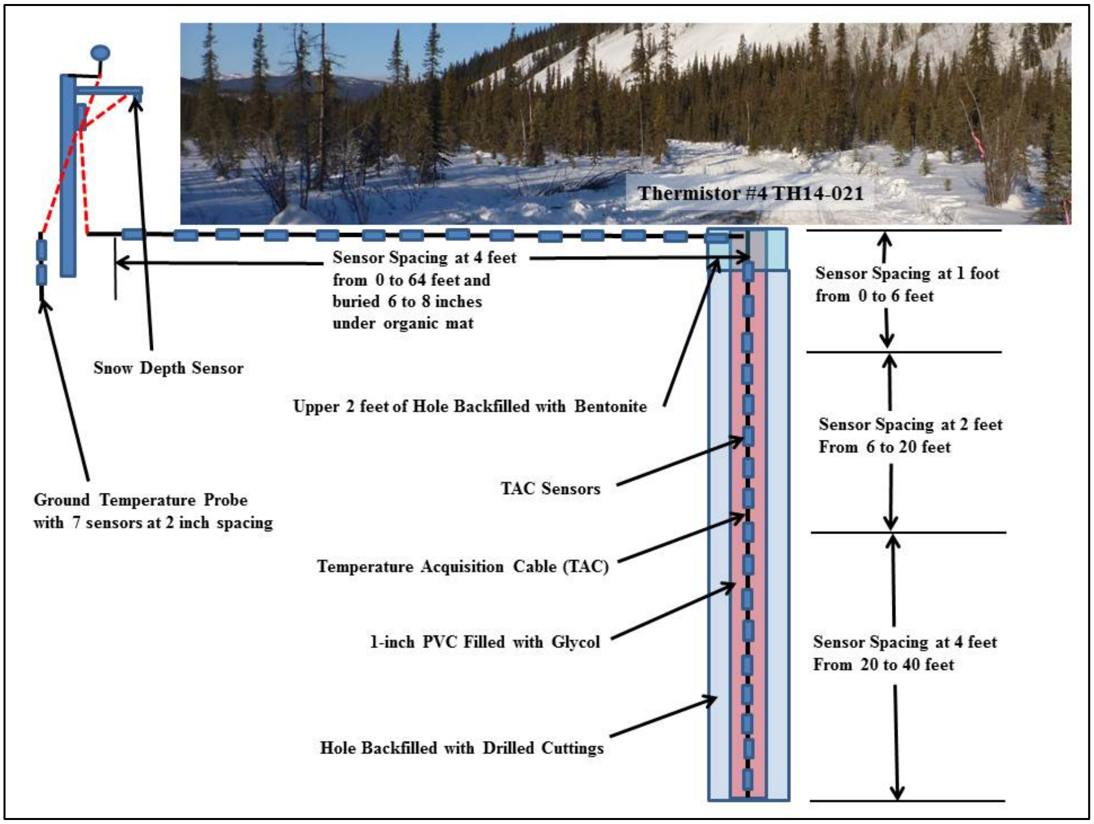


Figure 3. Typical Monitoring Station diagram.

Figure 4. Monitoring Station # 1.

On October 13, 2016, NRMS staff inspected Monitoring Station # 1. Test pits were dug and soil samples were obtained. Gravimetric water and organic contents were analyzed for each sample in the NRMS Laboratory. Thaw depth was determined using a steel-probe. Information obtained during the site visit and the laboratory data allowed for additional characterization of near-surface foundation soils.

Test Pit # 1 was dug near Monitoring Station # 1 in undisturbed tundra off the winter trail. Figures 5 through 7 illustrate the excavation in Test Pit # 1.

We observed the following soil sequence in Test Pit # 1:

- 6 inches of tundra
- 4 inches of moist to wet peat (Sample # 16-DH001: NM 244.4%; ORG 51.1%)
- 8 inches of wet organic-rich silt (Sample # 16-DH002: NM 101.4%; ORG 22.2%)
- Permafrost was hit at 18 inches below ground surface
- Ice-rich & organic-rich frozen silt was encountered between 1.5 to 2.0 feet (Sample # 16-DH003: NM 143.5%; ORG 15.9%)

Figure 5. Test Pit # 1.

Figure 6. Test Pit # 1.

Figure 7. Tundra removed from Test Pit # 1.

Test Pit # 2 was dug near Monitoring Station # 1 within the winter trail. Figure 8 illustrates the excavation in Test Pit # 2.

We observed the following soil sequence in Test Pit # 2:

- 6 inches of saturated and frozen tundra
- 7 inches moist to wet peat (Sample # 16-DH004: NM 334.0%; ORG 66.4%)
- 9 inches of wet organic-rich silt (Sample # 16-DH005: NM 79.4%; ORG 19.3%)
- Permafrost was hit at 22 inches below ground surface
- Ice-rich & organic-rich frozen silt was encountered between 1.6 to 2.0 feet (Sample # 16-DH006: NM 155.9%: ORG 20.7%)

Figure 8. Test Pit # 2.

Air and ground temperature measurements were obtained by telemetry service of BeadedStream between December 3, 2014 and December 27, 2017. The temperature record between December 3, 2014 and December 27, 2017 was reliably complete with only three records missing. Air temperatures and near-surface ground temperatures were compared to determine the n-factors for the undisturbed Black Spruce-tundra setting. Probing was conducted to determine thaw depth (Figure 9); results are shown in Table 1. Near-surface ground temperature records corroborate that the peat is saturated. The air temperature record was compared to the Livengood Airport

Station; air temperatures were generally 1 °F colder at the site as compared to the Livengood Airport Weather Station.

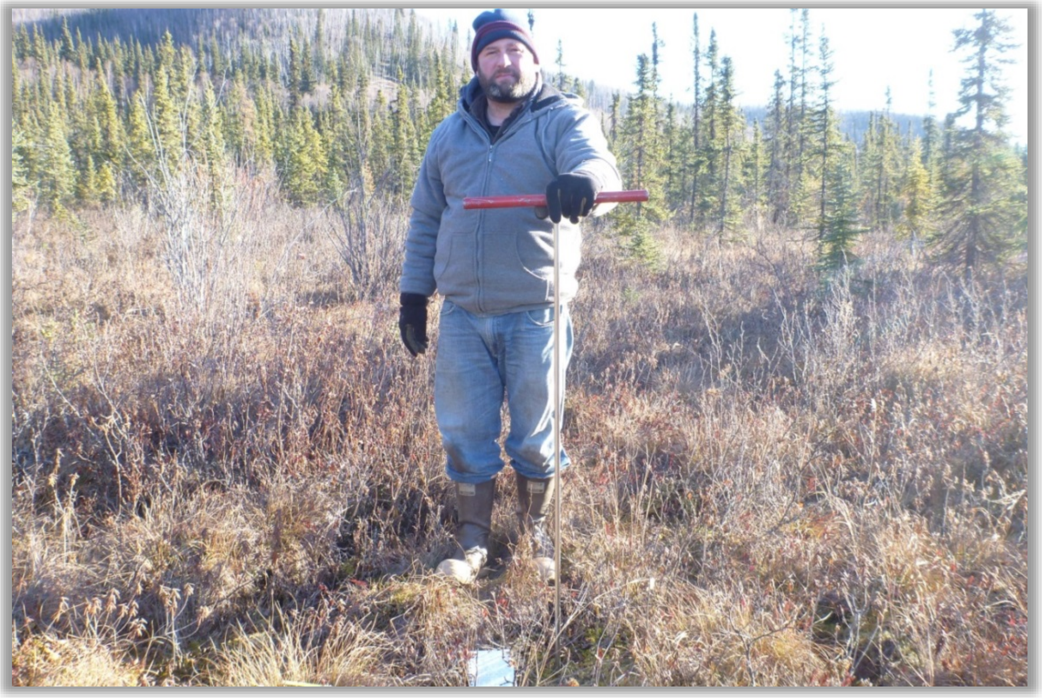


Figure 9. Soil probing of active layer.

Table 1– Thaw Depth at Monitoring Station # 1 on October 13, 2016

Location	**Thaw Depth (in)**		
	average	**median**	**standard deviation**
Undisturbed Black Spruce and tundra	20.9	20.5	2.5
Winter trail where trees had been cleared but little disturbance to tundra	21.9	22.0	2.1

There was very little difference between the thaw depth in undisturbed areas and the trail used for winter drilling that exhibited minimal disturbance of the tundra. Thaw-depth probing was repeated on August 31, 2017; results are shown in Table 2. There was 3.4 inch difference between the thaw depth in undisturbed area and the trail used for winter drilling. This represents a 19% increase in the thaw-depth; which is assumed to be the thickness of the active layer.

Table 2– Thaw Depth at Monitoring Station # 1 on August 31, 2017

Location	**Active Layer Thickness (in)**		
	average	**median**	**standard deviation**
Undisturbed Black Spruce and tundra	17.6	17.5	1.7
Winter trail where trees had been cleared but little disturbance to tundra	21.0	21.5	2.2

Monitoring Station # 2: BeadedStream Temp Site # 3 – TH14-053

TH14-053 was drilled on March 5, 2014 and encountered 1 foot of organic mat, 1 foot of ice-rich silt, 0.5 feet of peat, 5.5 feet of ice-rich organic silt with sand, 1 foot of organic silt, 2 feet of silty sand with gravel and 14 feet of sand with silt and gravel. Subsurface conditions encountered while drilling are shown on the Final Test Hole Log for TH14-053 as shown in Figure 10. Foundation soils were frozen to the depth explored.

Monitoring Station # 2 was established at borehole TH14-053. A temporary DTC was installed in TH14-053 on October 23, 2014. Air and ground temperatures to a depth of 21.5 feet bgs were recorded every 6 hours at the site starting on October 23, 2014. A single-point DTC in a radiation shield was installed to monitor air temperatures. A single-point DTC was installed to monitor soil-surface temperatures. A multi-sensor DTC was installed in TH14-053 to monitor ground temperatures at 1.5, 6.5, 11.5, 16.5, and 21.5 feet below ground surface. The air temperature sensor started failing on 9/7/16. The air temperature record was compared to the Livengood Airport Weather Station; air temperatures were generally 2 ºF colder at the site as compared to the Livengood Airport Station. Temperature monitoring was terminated on March 30, 2017. The temperature record was incomplete and was not used in thermal modeling efforts.

On October 14, 2016, NRMS staff inspected Monitoring Station # 2. Test pits were dug and soil samples were obtained. Gravimetric water and organic contents were analyzed for each sample in the NRMS Laboratory. Thaw depth was determined using a steel-probe; results are shown in Table 3.

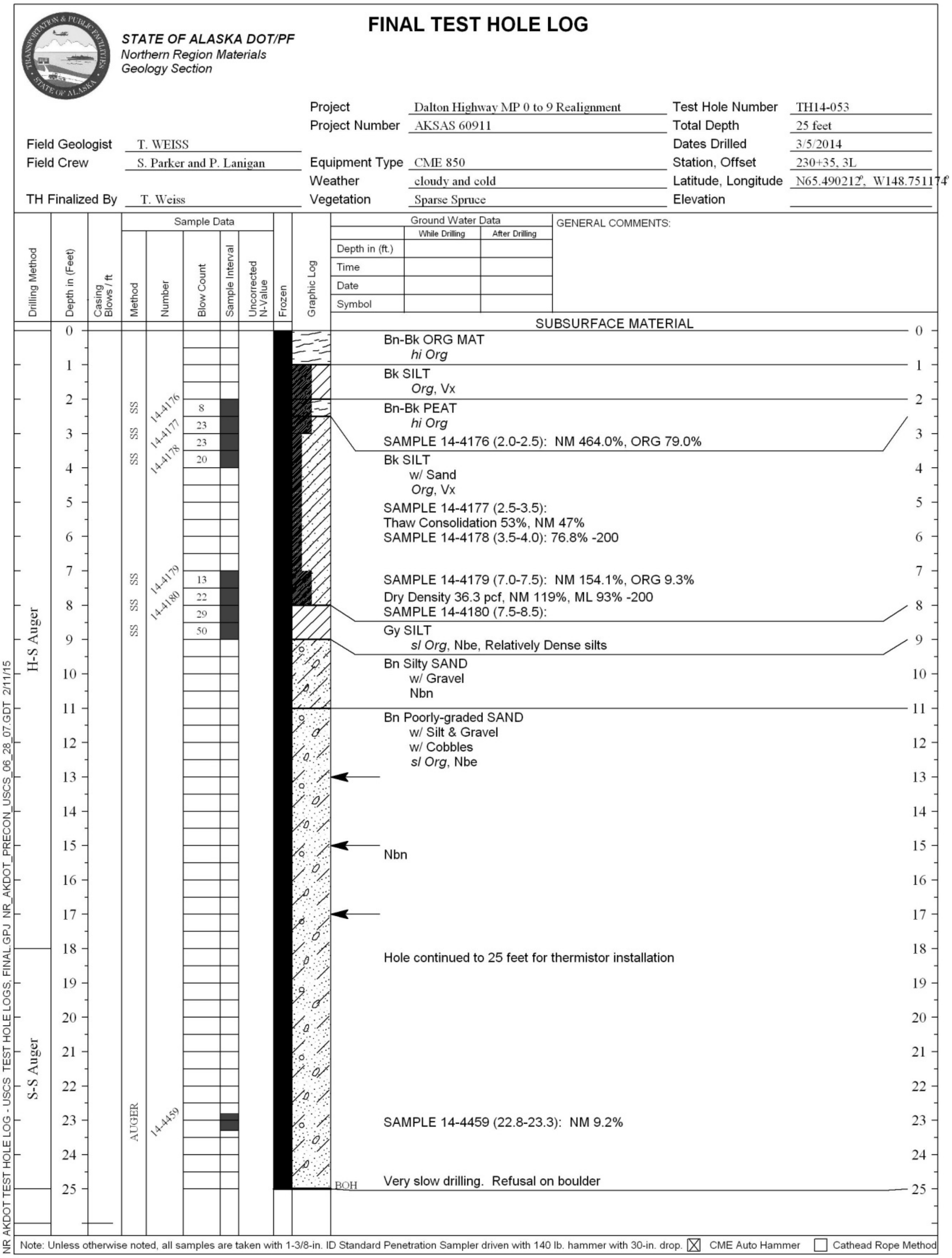
Table 3– Thaw Depth at Monitoring Station # 2 on October 14, 2016

Location	Thaw Depth (in)		
	average	median	standard deviation
Undisturbed Black Spruce and tundra north of winter trail	19.1	18.8	1.1
Undisturbed Black Spruce and tundra south of winter trail	19.4	19.8	1.6
Winter trail where trees had been cleared but little disturbance to tundra	21.1	20.8	1.7

There was very little difference between the thaw depth in undisturbed areas and the trail used for winter drilling that had minimal disturbance of the tundra.

Test Pit # 4 (Figure 11) was dug within the winter trail adjacent to Monitoring Station # 2 near TH14-053. We observed the following soil sequence in Test Pit # 4:

- 5.5 inches of tundra
- 13.5 inches of moist to wet peat (Sample # 16-DH010: NM 435.6%; ORG 80.8%)
- 1 inch of wet organic-rich silt (Sample #16-DH011: NM 75.9%; ORG 23.3%)
- Permafrost was encountered at 20 inches below ground surface
- Saturated conditions and infiltration of water prevented sampling of the frozen silt.



STATE OF ALASKA DOT/PF
Northern Region Materials
Geology Section

FINAL TEST HOLE LOG

Project: Dalton Highway MP 0 to 9 Realignment
Project Number: AKSAS 60911
Test Hole Number: TH14-053
Total Depth: 25 feet
Dates Drilled: 3/5/2014
Field Geologist: T. WEISS
Field Crew: S. Parker and P. Lanigan
Equipment Type: CME 850
Station, Offset: 230+35, 3L
Weather: cloudy and cold
Latitude, Longitude: N65.490212°, W148.751174°
TH Finalized By: T. Weiss
Vegetation: Sparse Spruce
Elevation:

Ground Water Data	While Drilling	After Drilling
Depth in (ft.)		
Time		
Date		
Symbol		

GENERAL COMMENTS:

Drilling Method	Depth in (Feet)	Casing Blows / ft	Method	Number	Blow Count
H-S Auger	2		SS	14-4176	8
			SS	14-4177	23
	3				23
			SS	14-4178	20
	7		SS	14-4179	13
			SS	14-4180	22
	8				29
			SS		50
S-S Auger	23		AUGER	14-4459	

SUBSURFACE MATERIAL

0–1: Bn-Bk ORG MAT
hi Org

1–2: Bk SILT
Org, Vx

2–2.5: Bn-Bk PEAT
hi Org
SAMPLE 14-4176 (2.0-2.5): NM 464.0%, ORG 79.0%

2.5–8: Bk SILT
w/ Sand
Org, Vx
SAMPLE 14-4177 (2.5-3.5):
Thaw Consolidation 53%, NM 47%
SAMPLE 14-4178 (3.5-4.0): 76.8% -200

SAMPLE 14-4179 (7.0-7.5): NM 154.1%, ORG 9.3%
Dry Density 36.3 pcf, NM 119%, ML 93% -200
SAMPLE 14-4180 (7.5-8.5):

8–9: Gy SILT
sl Org, Nbe, Relatively Dense silts

9–11: Bn Silty SAND
w/ Gravel
Nbn

11–25: Bn Poorly-graded SAND
w/ Silt & Gravel
w/ Cobbles
sl Org, Nbe

15: Nbn

Hole continued to 25 feet for thermistor installation

SAMPLE 14-4459 (22.8-23.3): NM 9.2%

25: BOH Very slow drilling. Refusal on boulder

Note: Unless otherwise noted, all samples are taken with 1-3/8-in. ID Standard Penetration Sampler driven with 140 lb. hammer with 30-in. drop. ☒ CME Auto Hammer ☐ Cathead Rope Method

NR AKDOT TEST HOLE LOG - USCS TEST HOLE LOGS, FINAL.GPJ NR_AKDOT_PRECON_USCS_06_28_07.GDT 2/11/15

Figure 10. Drill log for TH14-053.

Figure 11. Test Pit # 4.

Monitoring Station # 3: BeadedStream Permanent Site # 2 – TH15-2053

The NRMS installed a temporary DTC in TH14-103 on May 20, 2014. Ground temperatures were monitored until October 8, 2014. The NRMS installed a full-monitoring station near TH14-103 on December 3, 2014. A BeadedStream acoustic sensor was installed to monitor snow depth. A single-point DTC in a radiation shield was installed to monitor air temperatures. A multi-sensor 1-foot rigid DTC was installed to monitor soil near-surface temperatures. A 114-foot multi-sensor DTC was installed in TH14-103 to monitor ground temperatures at 1.2, 2.2, 3.2, 4.2, 6.2, 8.2, 10.2, 12.2, 14.2, 16.2, 18.2, 22.2, 26.2, 30.2, 34.2 and 38.2 feet below ground surface and soil-surface temperatures at 17 locations (at 4-foot intervals) between TH14-103 and the data-logger location. The DTC was installed in a flexible conduit between TH14-103 and the data logger and the conduit was placed on the surface of the tundra.

The DTC at Monitoring Station # 3 was originally installed in TH14-103. TH14-103 was drilled on March 21, 2014. It was drilled on undisturbed tundra that had the trees removed for drill rig access (Figure 12). The drill hole encountered 1 foot of organic mat, 8 feet of ice-rich organic silt, 8.5 feet of silt, and 2.5 feet of sand and gravel (BOH). Subsurface conditions encountered while drilling are shown on the Final Test Hole Log for TH14-021 in Figure 13. Foundation soils were frozen to the depth explored.

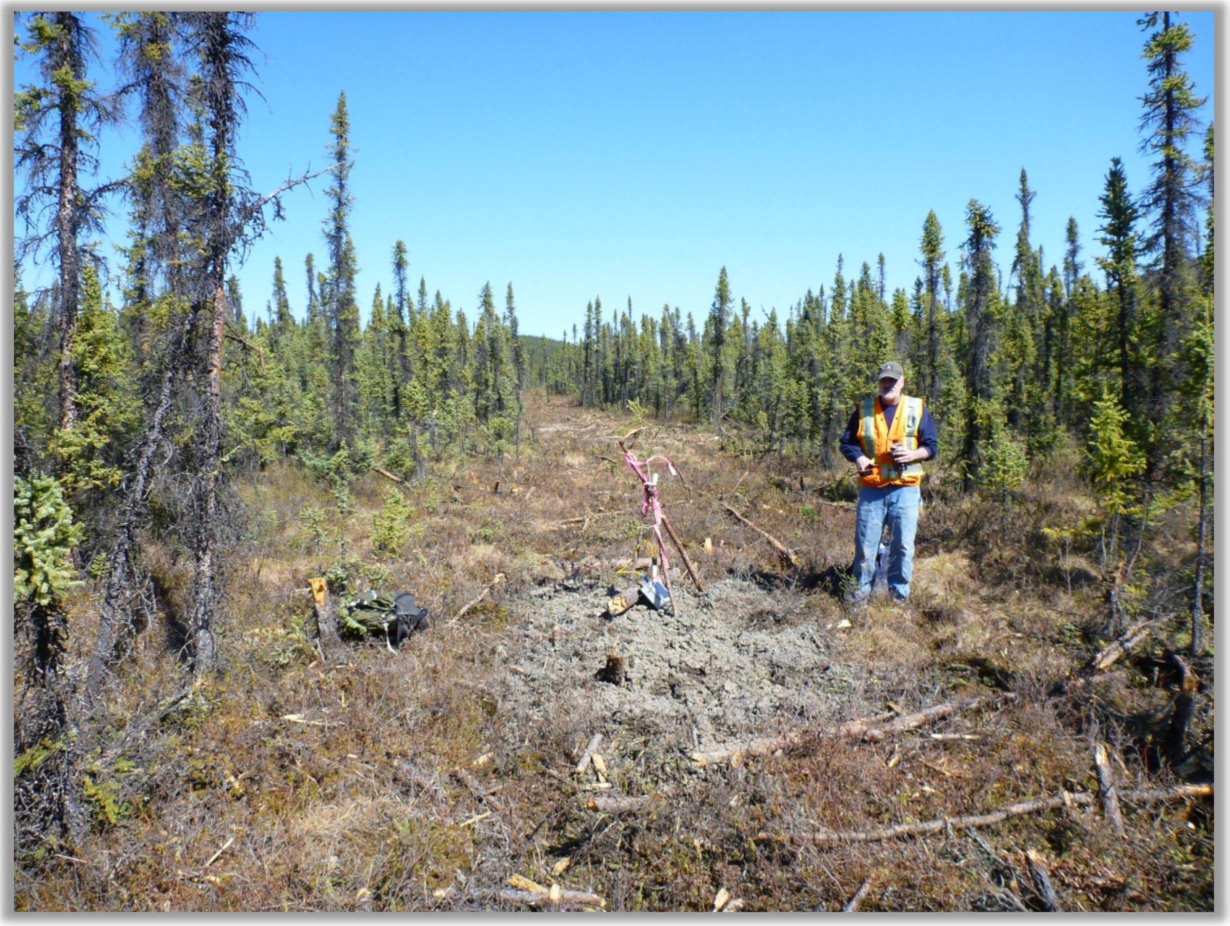
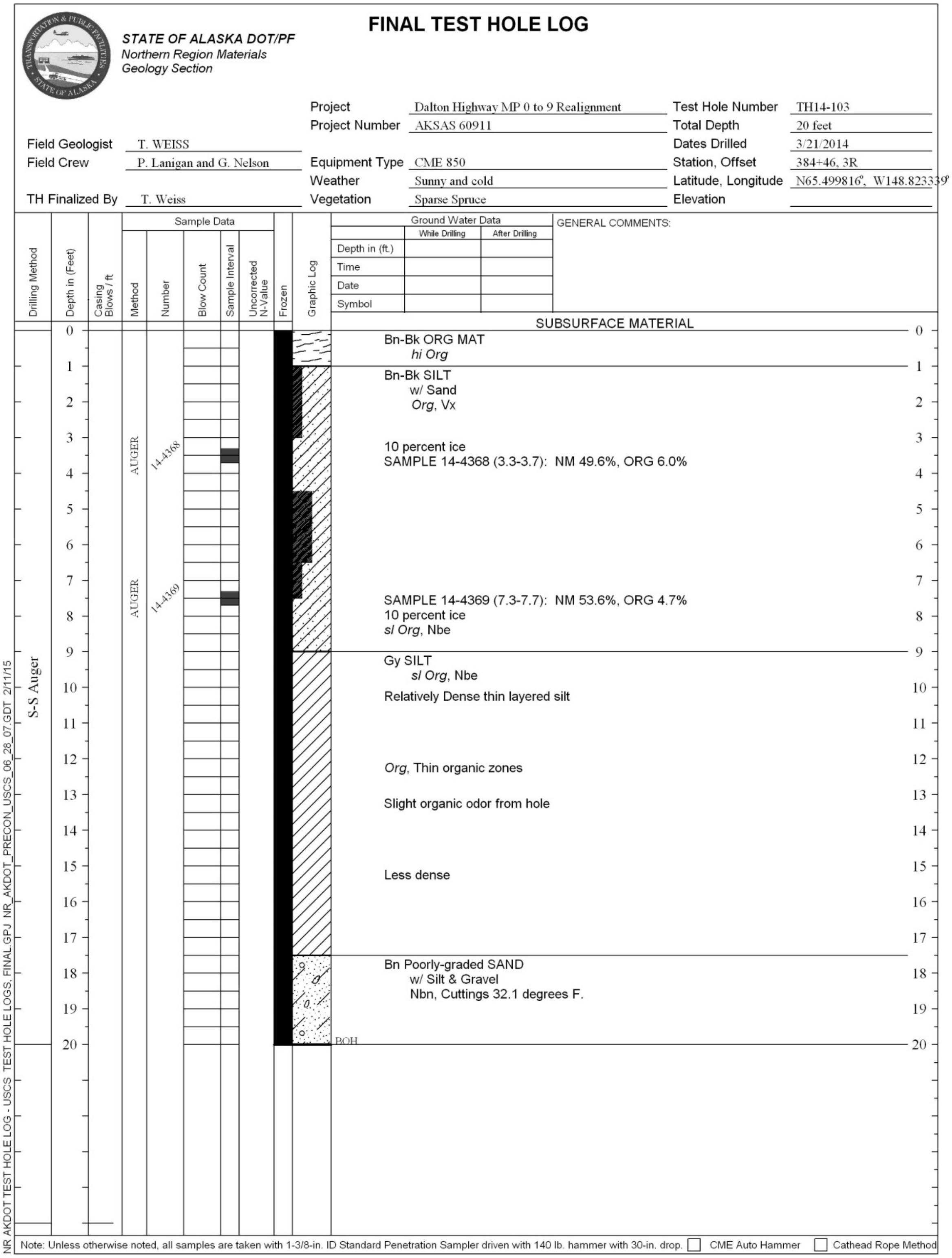


Figure 12. TH14-103.



STATE OF ALASKA DOT/PF
Northern Region Materials
Geology Section

FINAL TEST HOLE LOG

Project: Dalton Highway MP 0 to 9 Realignment
Project Number: AKSAS 60911
Test Hole Number: TH14-103
Total Depth: 20 feet
Field Geologist: T. WEISS
Dates Drilled: 3/21/2014
Field Crew: P. Lanigan and G. Nelson
Equipment Type: CME 850
Station, Offset: 384+46, 3R
Weather: Sunny and cold
Latitude, Longitude: N65.499816°, W148.823339°
TH Finalized By: T. Weiss
Vegetation: Sparse Spruce
Elevation:

	Ground Water Data	
	While Drilling	After Drilling
Depth in (ft.)		
Time		
Date		
Symbol		

GENERAL COMMENTS:

Drilling Method | Depth in (Feet) | Casing Blows / ft | Sample Data: Method, Number, Blow Count, Sample Interval, Uncorrected N-Value | Frozen | Graphic Log

Drilling Method: S-S Auger

Samples: AUGER 14-4368; AUGER 14-4369

SUBSURFACE MATERIAL

0
Bn-Bk ORG MAT
hi Org
1
Bn-Bk SILT
w/ Sand
Org, Vx
2
3
10 percent ice
SAMPLE 14-4368 (3.3-3.7): NM 49.6%, ORG 6.0%
4
5
6
7
SAMPLE 14-4369 (7.3-7.7): NM 53.6%, ORG 4.7%
10 percent ice
sl Org, Nbe
8
9
Gy SILT
sl Org, Nbe
Relatively Dense thin layered silt
10
11
12
Org, Thin organic zones
13
Slight organic odor from hole
14
15
Less dense
16
17
18
Bn Poorly-graded SAND
w/ Silt & Gravel
Nbn, Cuttings 32.1 degrees F.
19
20
BOH

Note: Unless otherwise noted, all samples are taken with 1-3/8-in. ID Standard Penetration Sampler driven with 140 lb. hammer with 30-in. drop. ☐ CME Auto Hammer ☐ Cathead Rope Method

NR AKDOT TEST HOLE LOG - USCS TEST HOLE LOGS, FINAL.GPJ NR_AKDOT_PRECON_USCS_06_28_07.GDT 2/11/15

Figure 13. Drill log for TH14-103.

TH15-2053 was drilled on July 15, 2015 on the new alignment near TH14-103. It encountered 0.5 feet of organic mat, 12 feet of ice-rich gray silt, and 25 feet of sand with silt and gravel (BOH). Subsurface conditions encountered while drilling are shown on the Final Test Hole Log for TH15-2053 is shown in Figure 14. Foundation soils were frozen from a depth of 1 foot to the depth explored.

Due to a minor shift in the planned road alignment to avoid particularly ice-rich soils, the DTC installed in TH14-103 was no longer under the proposed road embankment; therefore the 114-foot multi-sensor DTC was relocated from TH14-103 to TH15-2053 on September 10, 2015. Sensor locations in TH15-2053 are at 1.7, 2.7, 3.7, 4.7, 6.7, 8.7, 10.7, 12.7, 14.7, 16.7, 18.7, 22.7, 26.7, 30.7, 34.7 and 38.7 feet below ground surface and soil-surface temperature sensors are at 17 locations (at 4-foot intervals) between TH15-2053 and the data-logger location. The horizontal portion of the DTC was buried at the approximate mid-point of the tundra mat (generally 4 to 10 inches below the mat surface) on September 10, 2015. Snow depth and air and ground temperature monitoring occurred at the data-logger location since December 3, 2014. Ground temperature monitoring occurred in TH14-103 between December 3, 2014 and September 10, 2015. Ground temperature monitoring occurred in TH15-2053 since September 11, 2015. Note – it was determined that the Temperature Acquisition Cable (DTC) sensor depths listed on the BeadedStream web site require slight adjustment; these were not corrected as they were not used for thermal model calibration. Ground temperatures were measured in TH14-103 between December 3, 2014 and September 11, 2015. This DTC was relocated to TH15-2053 and began recording ground temperatures on September 11, 2015.

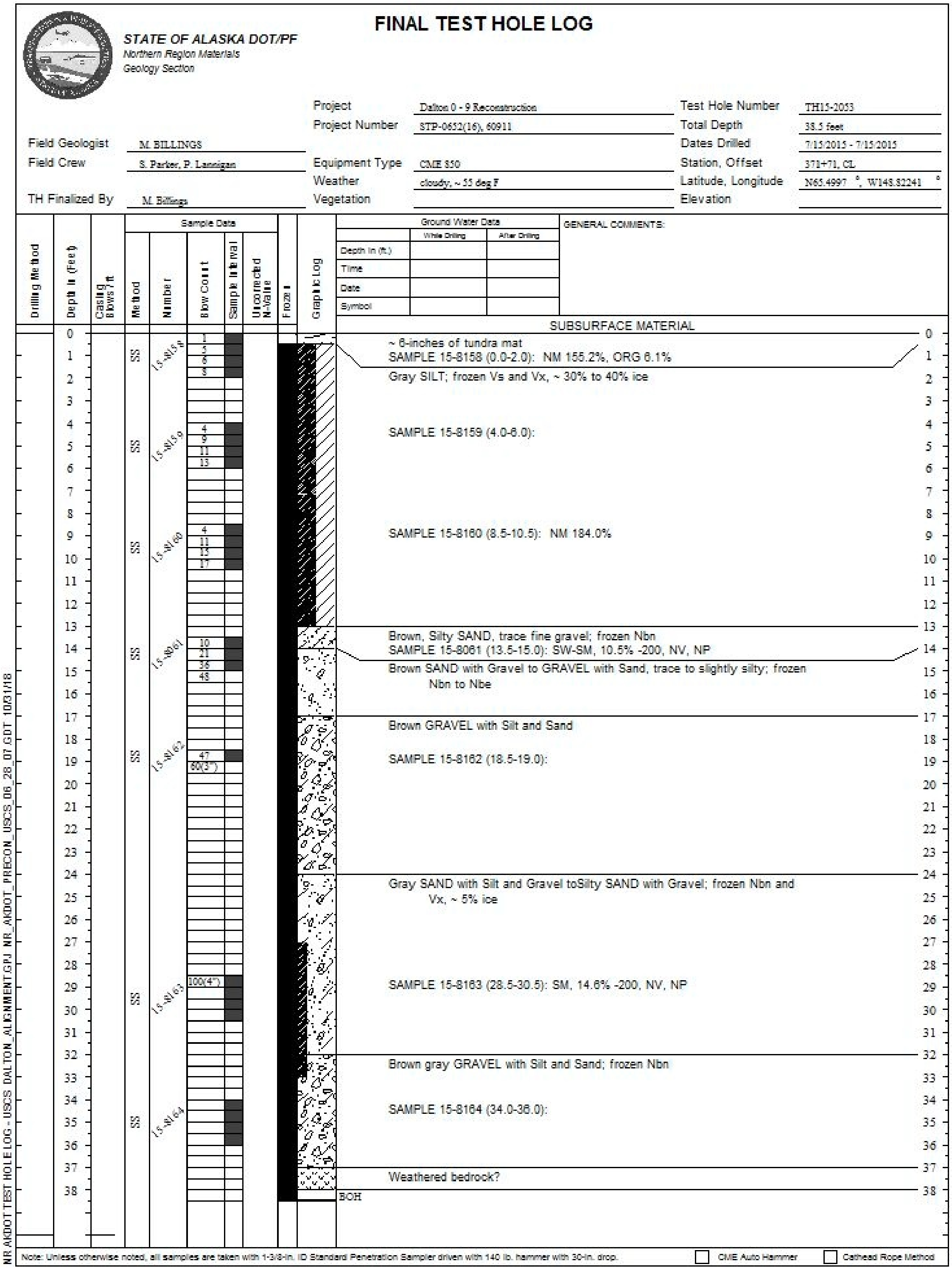
On October 13, 2016, Northern Regions Material Section (NRMS) staff inspected Monitoring Station # 3. Test pits were dug and soil samples were obtained. Gravimetric water and organic contents were analyzed for each sample in the NRMS Laboratory. Thaw depth was determined using a steel-probe.

Test Pit # 3 (Figure 15) was dug in undisturbed tundra off the access trail adjacent TH15-2053.

We observed the following soil sequence in Test Pit # 3:

- 5 inches of tundra
- 6 inches of moist to wet peat (Sample # 16-DH007: NM 299.5%; ORG 49.8%)
- 6.5 inches of wet gray silt (Sample # 16-DH008: NM 33.5%; ORG 4.2%)
- Permafrost was encountered at 17.5 inches below ground surface
- Ice-rich frozen silt was encountered between 1.5 to 2.0 feet (Sample # 16-DH009: NM 139.6%; ORG 4.5%)

Probing was conducted to determine thaw depth (Figure 16); results are shown in Table 4. There was a significant difference between the thaw depths in the undisturbed areas vs. at TH15-2053, which was drilled during the summer of 2015.



FINAL TEST HOLE LOG

STATE OF ALASKA DOT/PF
Northern Region Materials
Geology Section

Project: Dalton 0 - 9 Reconstruction
Project Number: STP-0652(16), 60911
Test Hole Number: TH15-2053
Total Depth: 38.5 feet
Field Geologist: M. BILLINGS
Dates Drilled: 7/15/2015 - 7/15/2015
Field Crew: S. Parker, P. Lannigan
Equipment Type: CME 850
Station, Offset: 371+71, CL
Weather: cloudy, ~ 55 deg F
Latitude, Longitude: N65.4997 °, W148.82241 °
TH Finalized By: M. Billings
Vegetation:
Elevation:

Ground Water Data

	While Drilling	After Drilling
Depth in (ft.)		
Time		
Date		
Symbol		

GENERAL COMMENTS:

Sample Data

Drilling Method	Depth in (Feet)	Casing Blows / ft	Method	Number	Blow Count	Sample Interval	Uncorrected N-Value	Frozen	Graphic Log
	0.0-2.0		SS	15-8158	1 5 6 8				
	4.0-6.0		SS	15-8159	4 9 11 13				
	8.5-10.5		SS	15-8160	4 11 15 17				
	13.5-15.0		SS	15-8061	10 21 36 48				
	18.5-19.0		SS	15-8162	47 60(3")				
	28.5-30.5		SS	15-8163	100(4")				
	34.0-36.0		SS	15-8164					

SUBSURFACE MATERIAL

0
~ 6-inches of tundra mat
SAMPLE 15-8158 (0.0-2.0): NM 155.2%, ORG 6.1%
Gray SILT; frozen Vs and Vx, ~ 30% to 40% ice
SAMPLE 15-8159 (4.0-6.0):
SAMPLE 15-8160 (8.5-10.5): NM 184.0%
13
Brown, Silty SAND, trace fine gravel; frozen Nbn
SAMPLE 15-8061 (13.5-15.0): SW-SM, 10.5% -200, NV, NP
Brown SAND with Gravel to GRAVEL with Sand, trace to slightly silty; frozen Nbn to Nbe
17
Brown GRAVEL with Silt and Sand
SAMPLE 15-8162 (18.5-19.0):
24
Gray SAND with Silt and Gravel toSilty SAND with Gravel; frozen Nbn and Vx, ~ 5% ice
SAMPLE 15-8163 (28.5-30.5): SM, 14.6% -200, NV, NP
32
Brown gray GRAVEL with Silt and Sand; frozen Nbn
SAMPLE 15-8164 (34.0-36.0):
37
Weathered bedrock?
38
BOH

Note: Unless otherwise noted, all samples are taken with 1-3/8-in. ID Standard Penetration Sampler driven with 140 lb. hammer with 30-in. drop.   ☐ CME Auto Hammer   ☐ Cathead Rope Method

NR AKDOT TEST HOLE LOG - USCS DALTON_ALIGNMENT.GPJ NR_AKDOT_PRECON_USCS_06_28_07.GDT 10/31/18

Figure 14. Drill Log for TH15-2053.

Figure 15. Test Pit # 3.

Figure 16. Soil probing near TH15-2053.

Table 4– Thaw Depth at Monitoring Station # 3 on October 13, 2016

Location	Thaw Depth (in)		
	average	median	standard deviation
Significant surface disturbance, compressed tundra and apparent thaw-subsidence from summer drilling	34.1	34.0	2.0
Less-disturbed section of trail with possible only a single-pass of the drill rig	18.1	18.0	1.5
Undisturbed Black Spruce and tundra	18.9	19.5	1.8

On October 13, 2016, there was very little difference between the thaw depths in undisturbed areas vs. the access trail with minimal disturbance. There was almost double the thaw depth between the areas disturbed by summer drilling operations vs. the undisturbed areas. Thaw-depth probing was repeated on August 31, 2017; results are shown in Table 5.

Table 5– Thaw Depth at Monitoring Station # 3 on August 31, 2017

Location	**Thaw Depth (in)**		
	average	**median**	**standard deviation**
Significant surface disturbance, compressed tundra and apparent thaw-subsidence from summer drilling	35.4	36.0	2.1
Less-disturbed section of trail with possible only a single-pass of the drill rig	19.0	18.5	3.2
Undisturbed Black Spruce and tundra	17.7	17.5	1.8

On August 31, 2017, there was very little difference between the thaw depths in undisturbed areas vs. the access trail with minimal disturbance. There was double the thaw depth between the areas disturbed by summer drilling operations vs. the undisturbed areas.

The summer drilling appears to have compressed the tundra mat and changed the n-factors of the surface near the borehole (Figure 17). The area near the borehole appears to have settled since the drilling occurred in 2015. Near-surface ground temperature records appear to corroborate that the peat is saturated. The air temperature sensor began to fail on 9/11/15 and was replaced on 10/31/15. The air temperature record was compared to the Livengood Airport Weather Station; air temperatures were generally 3 ºF colder at the site as compared to the Livengood Airport Weather Station.

Figure 17. Area around TH15-2053. Tundra was compressed during summer drilling.

Thermal Model Development

This section is intended to summarize our methods for analyzing the temperature regime along the proposed Dalton Highway MP 0 – 6 Realignment. This work was done as a portion of the effort for the Geotechnical Asset Management Thermal Modeling Research Project and also development of geotechnical recommendations regarding road embankment design for the Dalton Highway MP 0 – 9 Reconstruction Project.

Thermal Model Development

Our thermal models were developed using GeoStudio Temp/W, a commonly used, finite-element thermal modeling computer software program. We first modeled in-situ conditions using past temperature records, and current air and subsurface temperatures measured at three monitoring stations within the planned alignment. We then modeled several embankment configurations using projected future temperatures and several input parameters; such as surface boundary conditions and soil thermal properties; developed while calibrating our in-situ thermal models. The following subsections detail the model mesh / finite element geometry, location and data collected at each of our three monitoring stations, calibration of our in-situ models and development of our model input, and the results of our future embankment models.

Model Mesh Pattern and Finite Element Geometry

The size and shape of the finite elements within our models were defined by a mesh pattern. In general, we selected mesh patterns that resulted in larger elements near the bottom and finer elements near the top of our models. We chose such an element size distribution to reduce calculation time while maintaining relatively high data resolution near the surface. In addition, the thickness of model layers controlled the maximum size of the mesh pattern within particularly thin layers such as some of the near surface soil layers and insulation board within modeled embankments. In order to maintain acceptable accuracy in model calculations, we selected mesh patterns that resulted in finite element geometries that were both as equidimensional as possible and facilitated smooth geometric transitions through layer boundaries.

Although our mesh patterns varied amongst the varying models, we generally selected patterns that tapered from 7.5 feet to 5 feet near the bottom to 0.25 feet to 0.5 feet near the surface. We used rectangular-shaped mesh patterns within many layers. However, where large geometric transitions were necessary either between layers with contrasting thickness or within layers that had non-uniform geometries, we commonly used triangular-shaped mesh patterns. The reason for this is that we observed that triangular-shaped mesh patterns transitioned well while maintaining relatively equidimensional finite elements.

Temperature Monitoring Stations (Additional Descriptions)

Temperature monitoring stations were installed at three sites, designated as Monitoring Station # 1 (MS1), Monitoring Station # 2 (MS2), and Monitoring Station # 3 (MS3), along the proposed Dalton Highway Realignment. Each station consisted of a battery- and solar-powered, BeadedStream data logger as well as various Digital Temperature Cables (DTCs). Monitoring Station # 1 and Monitoring Station # 3 were configured with an approximate 114-foot-long DTC, an approximate 3.3-meter DTC, and a single-point DTC. The approximate 114-foot-long DTCs at these monitoring stations were installed such that portions of their length were installed within a vertical test hole while the remaining portions were installed horizontally just below the tundra-surface between the test hole and the data logger. The approximate 3.3-meter-long DTCs at these monitoring stations were installed vertically to a depth of approximately 1-foot below ground surface within a relatively undisturbed portion of tundra near the data logger. The single point DTCs at these monitoring stations were installed within a radiation shields roughly 5 feet to 6 feet above ground.

Monitoring Station # 2 was configured with an approximate 35-foot-long DTC, and two single-point DTCs. Roughly 21.5 feet of the 35-foot-long DTC was installed in a nearby vertical test hole while the remaining length was placed above ground. The data collected by the above ground sensors within this DTC was ignored in our analysis. One of the two single-point sensors at this site was installed roughly 4 feet to 5 feet above the ground surface within a radiation shield while the other single-point sensor was buried roughly 1 foot beneath the tundra surface. Table 6 summarizes the data logger and DTC configurations at each of the monitoring stations. Figure 18 illustrates the average daily air and near-surface soil temperature measured at a depth of 2.0 inches below the tundra-soil interface derived for Monitoring Site # 1.

Table 6- Summary of Monitoring Station Configurations

Monitoring Station	35-Foot DTC		114-Foot DTC				Vertical, 3.3-meter DTC		Single Point DTC	
			Vertical Portion		Horizontal Portion					
	Depth (ft)	Sensors (#)	Depth (ft)	Sensors (#)	Length (ft)	Sensors (#)	Depth (ft)	Sensors (#)	Air	Soil
MS1 TH14-021	N/A	N/A	~39.5	18	~70	17	~1	7	✓	N/A
MS2 TH14-053	~21.5	5	N/A	N/A	N/A	N/A	N/A	N/A	✓	✓
MS3 TH14-103 (12/05/14 – 09/10/15) TH15-2053 (09/11/15 – current)	N/A	N/A	~38.5	17	~70	18	~1	7	✓	N/A

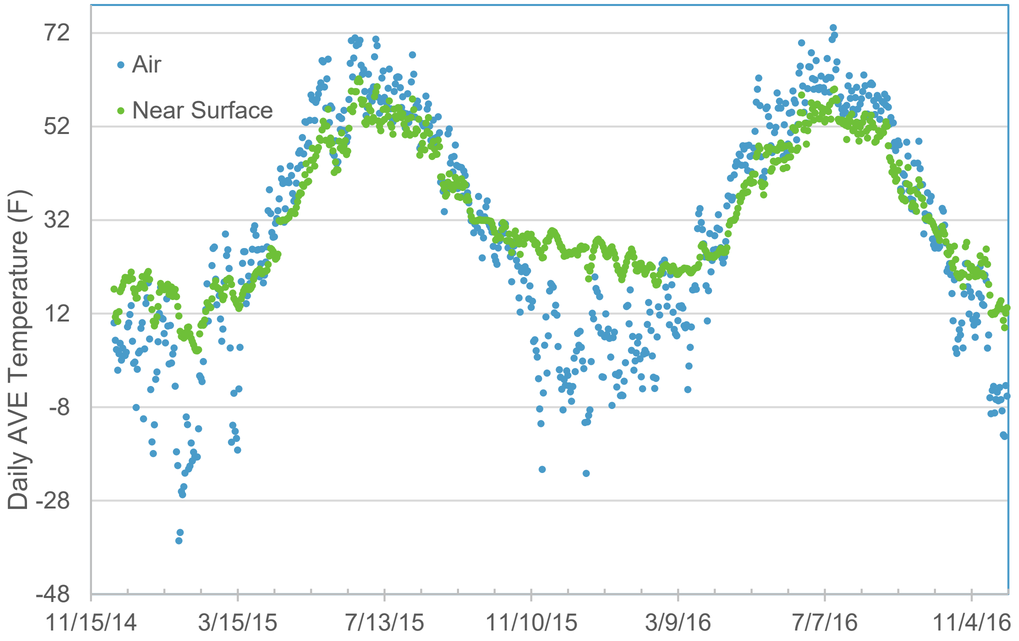


Figure 18. Average Daily Air and Near-Surface* Ground Temperatures Monitoring Station # 1.
* – Near-surface ground temperature was measured 2.0 inches below the tundra-soil interface.

Given the more complete air temperature record, longer ground temperature records in a given test hole and the greater sampling and laboratory testing that was conducted at TH14-021, TEMP/W modeling was conducted and calibrated for the foundation soil profile found at TH14-021.

In-situ Foundation Soil Thermal Models and Development of Model Inputs

Prior to running models for predicted future air temperatures, we calibrated our model inputs by modeling in-situ condition at Monitoring Station #1. This calibration was achieved by applying a subsurface temperature profile as the initial condition, running predicted historical, 50-yearlong air temperature record, and adjusting both boundary conditions and soil thermal properties to a point where results were plausible and within close agreement to that observed through our measured data.

Another portion of this process was observing model results amongst several subsequent years leading up to the present and analyzing whether a relative temperature equilibrium had been established. We conducted these calibration steps for both a 50-yearlong and 100-yearlong predicted temperature record and observed that both resulted in a relative equilibrium and essentially the same subsurface temperature profiles.

Surface Boundary Condition and Development of n-factors

The surface boundary condition used in our model was defined by the daily surface temperature throughout the modeled time duration. These daily surface temperatures were developed by modifying the daily air temperature with the thawing and freezing n-factors, which are the ratios of the surface and air thawing and freezing indices, respectively. These n-factors are calculated with the following equations:

$$n_T = \frac{TI_s}{TI_a};\ n_F = \frac{FI_s}{FI_a}$$

TI_a and TI_s are the air and surface thawing indexes, respectively. These thawing indices are expressed in degree-days and are a measure of the cumulative degrees above freezing during the thaw-season. FI_a and FI_s are the air and surface freezing indices, respectively. These freezing indices are expressed in degree-days and are a measure of the cumulative degrees below freezing during the freezing-season. The thawing and freezing indices are calculated via the following equations:

$$TI = \sum_{annual} TDD;\ TDD = degrees\ above\ freezing\ for\ each\ day\ within\ thaw\text{-}season$$

$$FI = \sum_{annual} FDD;\ FDD = degrees\ below\ freezing\ for\ each\ day\ within\ thaw\text{-}season$$

Daily surface temperatures for each surface boundary condition were then calculated via the following equation:

$$T_s = \{(n\text{-}factor) \times (T_a - 32)\} + 32;\ T_s\ and\ T_a\ are\ the\ air\ and\ surface\ temperature\ respectively$$

Monitoring Station #1 lies near the center of the proposed alignment. This location also lies near the center of an approximate 20- foot wide clearing where spruce trees have been removed and tundra is slightly disturbed due to use as a winter trail (Figure 19).   Along the margins of this slightly-disturbed clearing lies undisturbed tundra that is vegetated with brush and sparse black spruce. Soil surface temperatures in the slightly disturbed clearing, and the nearby-undisturbed tundra were measured via the 114-foot DTC, and the 3.3-meter DTC, respectively.

Figure 19. Active layer probing in center of winter trail near Monitoring Station # 1.

These two temperature profiles differed slightly. We developed, therefore, two different surface boundary conditions for the undisturbed and slightly-disturbed portions of tundra. These two surface boundary conditions were developed by comparing air and surface temperatures from our two-year record, calculating n-factors, and modifying the air temperature used within our model with these calculated n-factors. As with many of our steps while developing our model, this process was iterative, and our n-factors were adjusted during model calibration. Snow depths at

Monitoring Stations # 1 and #3 were measured with acoustic sensors; snow depth varied at sites, between sites and between years to the extent that is was not appropriate to attempt to incorporate snow depth as a stand-alone variable in the estimation of n-factors. Table 7 illustrates our final n-factors for the slightly disturbed and undisturbed tundra surfaces.

Table 7- n-factors for ground cover type in Thermal Models

Surface	n_{thaw}	n_{freeze}
Slightly Disturbed Tundra	0.92	0.47
Undisturbed Tundra	0.71	0.46

Subsurface Profile and Soil Thermal Properties

The test hole in which the vertical DTC at Monitoring Station #1 was installed was drilled with an approximate 6-inch diameter solid-stem auger. During drilling, a field geologist logged the subsurface conditions and collected soil samples for laboratory testing. The soil conditions as well as laboratory testing results for this location are illustrated in the test hole log for TH14-021 (Figure 2).

We developed a general soil profile for this site in accordance to the field descriptions and laboratory test results illustrated in the test hole log for TH14-021. The soil thermal properties used during our thermal model calibration were developed from a combination of using laboratory testing results, referring to literature and other resources, making reasonable assumptions, and employing an iterative approach between analyzing model results and adjusting estimated soil thermal properties.

During this process, we developed a spreadsheet that calculated soil thermal properties in accordance to methods described by Côté and Konrad (2005). As such, this spreadsheet required input of organic content, gravimetric moisture content, dry-density, and the temperature-dependent unfrozen moisture-content of soil – all of which were either determined from laboratory testing or estimated. An example of this spreadsheet is illustrated in Appendix A. Table 8 summarizes estimated thermal properties for the foundation soil profile developed while calibrating our thermal model.

We calibrated our model by adjusting soil thermal properties through comparison of modeled and measured freezing and thawing indices with depth, as well as the modeled and measured time-dependent temperature profile at the base of each soil layer. Our n-factors and our soil thermal properties were adjusted to approximate a best fit between these modeled and measured values.

Table 8- Summary of Subsurface Soils and Estimated Thermal Properties

Depth interval (ft)	Interval thickness (ft)	Soil description	Dry-unit Weight (γ, lb/ft^3)	Organic Content (%)	Moisture		Thermal conductivity (Btu/ft-day-°F)		Heat capacity (Btu/ft^3-°F)	
					Gravimetric w%	Volumetric Θ%	k_u	k_f	C_u	C_f
0 0.25	0.25	Live tundra mat	14**	100**	218**	48**	3	5	36	21
0.25 0.5	0.25	Dead tundra mat	22**	100**	170**	62**	5	11	49	30
0.5 1.0	0.5	Silty PEAT	18**	59*	289*	84**	6	16	53	29
1.0 1.75	0.75	Thawed organic SILT	46*	21*	90*	67**	9	24	49	51
1.75 3.0	1.25	Ice-rich SILT	32**	18*	150*	78**	11	31	56	32
3.0 8.0	5.0	Slightly ice-rich SILT	37**	12*	129*	76**	12	31	55	32
8.0 13.0	5.0	SILT; Nbe	52**	9**	80*	66*	13	31	52	32
13.0 25.0	8.0	SILT; Nbn	83**	5*	36*	48**	18	33	45	31
25.0 36.0	11.0	SAND with Silt and Gravel; Nbe	116**	2*	16*	29**	25	36	38	29
36.0 50.0	14.0	GRAVEL with Silt and Sand; with Cobbles	123**	2*	13*	25**	26	36	37	29

Notes:
* value based upon laboratory testing
** value was estimated

Lower Boundary Condition

During our two-year recording period, we observed a constant temperature of 28.5 °F at roughly 30 feet below the surface in Monitoring Station #1. During model calibration, we developed a model that was 30 feet deep and assigned this constant temperature to the lower boundary condition. We then adjusted other parameters such as n-factors and soil thermal properties until the modeled subsurface temperature profile coincided with that of the measured.

We next removed the constant-temperature boundary condition, increased the model depth to 50 feet and applied a heat-flux lower boundary condition. The purpose of using a heat flux boundary condition rather than constant temperature was to simulate the existing geothermal gradient and allow the temperature at this depth to adjust in accordance to a future thermal regime (i.e. various embankments and varying climate). Initially, a heat-flux of 0.6 Btu/day*ft^2, as suggested by *The Updated Heat Flow Map of Alaska* (Figure C-2, Appendix C), was applied.

The model was once again calibrated using the n-factors and soil properties developed from the previous step and adjusting the heat-flux to the point where the modeled subsurface thermal regime coincided with that measured. Thermal model calibration was achieved when the modeled subsurface temperature distribution, thaw-depth, and subsurface distribution of freezing and thawing indices coincided with that measured. This calibration was achieved where the lower boundary condition was set as a heat-flux of 0.35 Btu/day*ft^2. Figures 20 and 21 illustrate the depth distribution of both measured and modeled minimum and maximum temperatures and cumulative thawing and freezing days, at model calibration, for a period of record between December 4, 2014 and December 3, 2016, respectively.

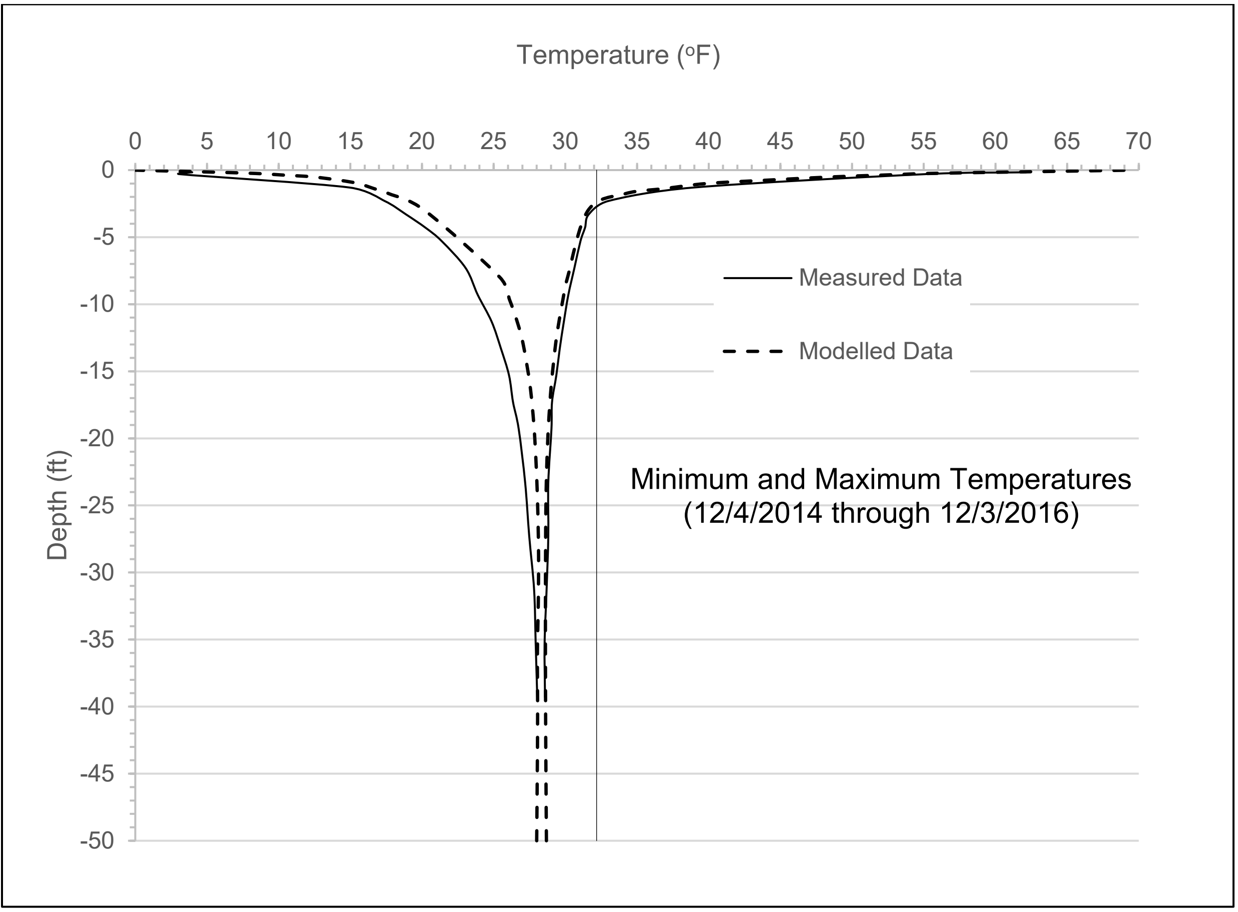


Figure 20. Measured and modeled minimum & maximum temperature profile.

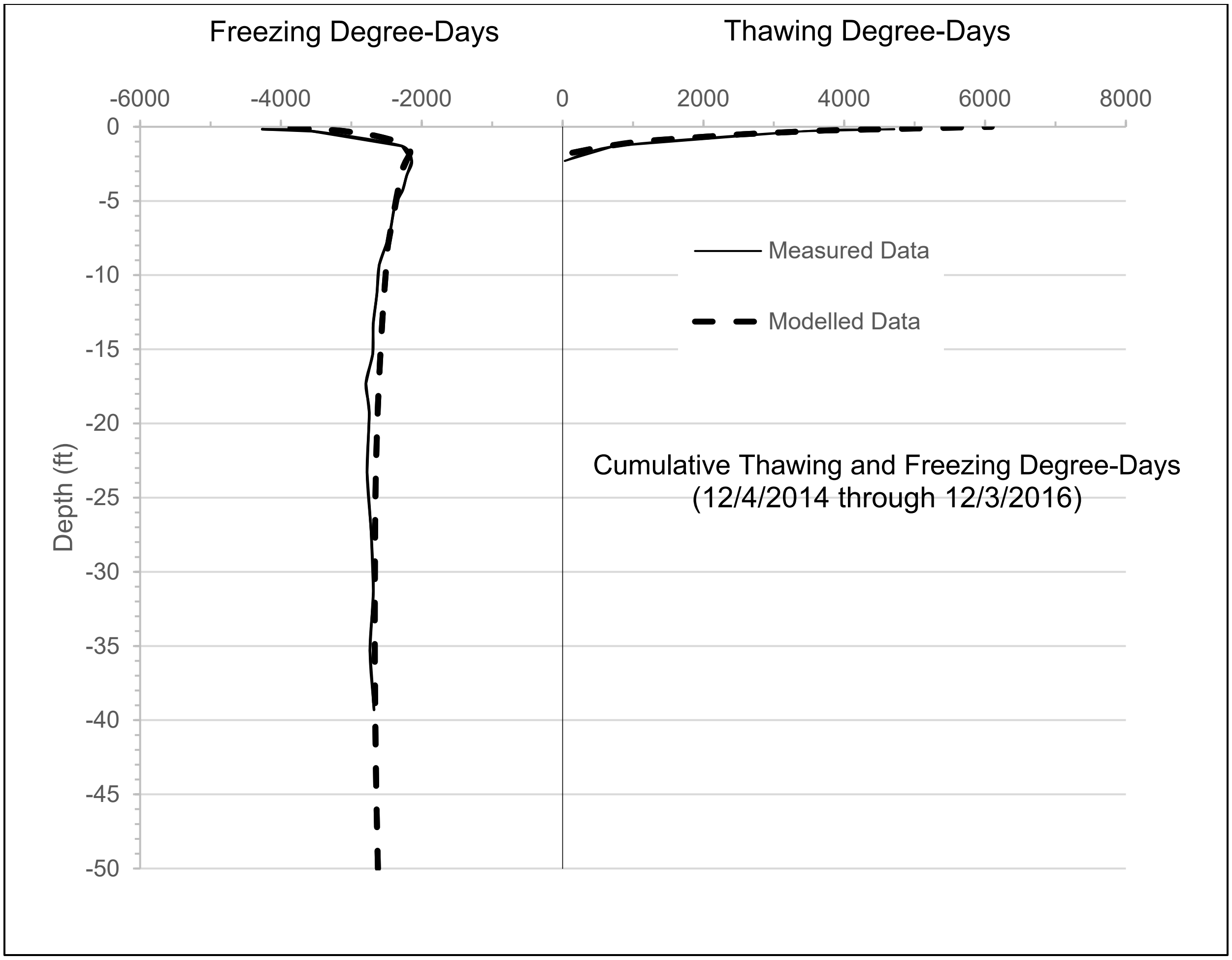


Figure 21. Measured and modeled cumulative thawing and freezing degree days.

Thermal Models of Road Embankments

We ran models for eight different road embankment configurations, all with a 39-foot-wide gravel surface. Each of these had a unique combination of embankment height, shoulder slope, and presence of a stabilization berm. Each of these eight embankment configurations were modeled with either no insulation, or 4 inches, 6 inches, 8 inches, 10 inches, and 12 inches of insulation. The following list summarizes the geometry for each of the eight embankment configurations modeled:

- 5-foot tall, 2H:1V slope, no stabilization berm
- 5-foot tall, 3H:1V: slope, no stabilization berm
- 5-foot tall, 2H:1V slope, stabilization berm
- 5-foot tall, 3H:1V: slope, stabilization berm
- 8-foot tall, 2H:1V slope, no stabilization berm
- 8-foot tall, 3H:1V: slope, no stabilization berm

- 8-foot tall, 2H:1V slope, stabilization berm
- 8-foot tall, 3H:1V: slope, stabilization berm

These models were run between May 1, 2016 and April 30, 2038, the first approximately two years of which were run without the embankment in order to ensure subgrade thermal equilibrium. Road embankment construction was assumed to occur in stages between October 1, 2018 and April 30, 2019. The completed embankment was modeled through April 30, 2038. This 19-year time duration included 18 thaw-seasons. Our model stages included:

- May 1, 2016 to October 1, 2018: No embankment, in-situ conditions
- October 1, 2018: Construction of an approximate 18-inch gravel embankment "working platform"; it was assumed the lower 12-inches would settle below original grade due to the compression of the underlying organic material
- March 14, 2019: Construct lower portion of embankment. Where applicable; this portion of the embankment contains layer(s) of foam board insulation
- April 30, 2019: Construct and finish upper portions of embankment

The projected temperature profile used in these models was developed by applying a temperature increase to a 365-day cycle. This 365-day cycle was developed by averaging 8 years of daily temperatures recorded at the nearby Livengood Airport temperature monitoring station and subtracting 1°F to adjust the Livengood Airport temperatures to temperatures at Monitoring Station # 1. This 365-day temperature profile was then projected forward with a temperature increase that approximates that predicted by the SNAP (Scenarios Network for Alaska + Arctic Planning) RCP 6.0 mid-level emissions model for air temperature increases through 2050. The predicted 365-day temperature profile for 2050 was then repeated for 19 years; this was done to add conservatism to the thaw-depth predictions. Figure 22 illustrates the temperature profile used to model the thermal impacts of road construction on the underlying foundation soils between May 1, 2016 and April 30, 2038 assuming a repeat of our projected 2050 air temperatures.

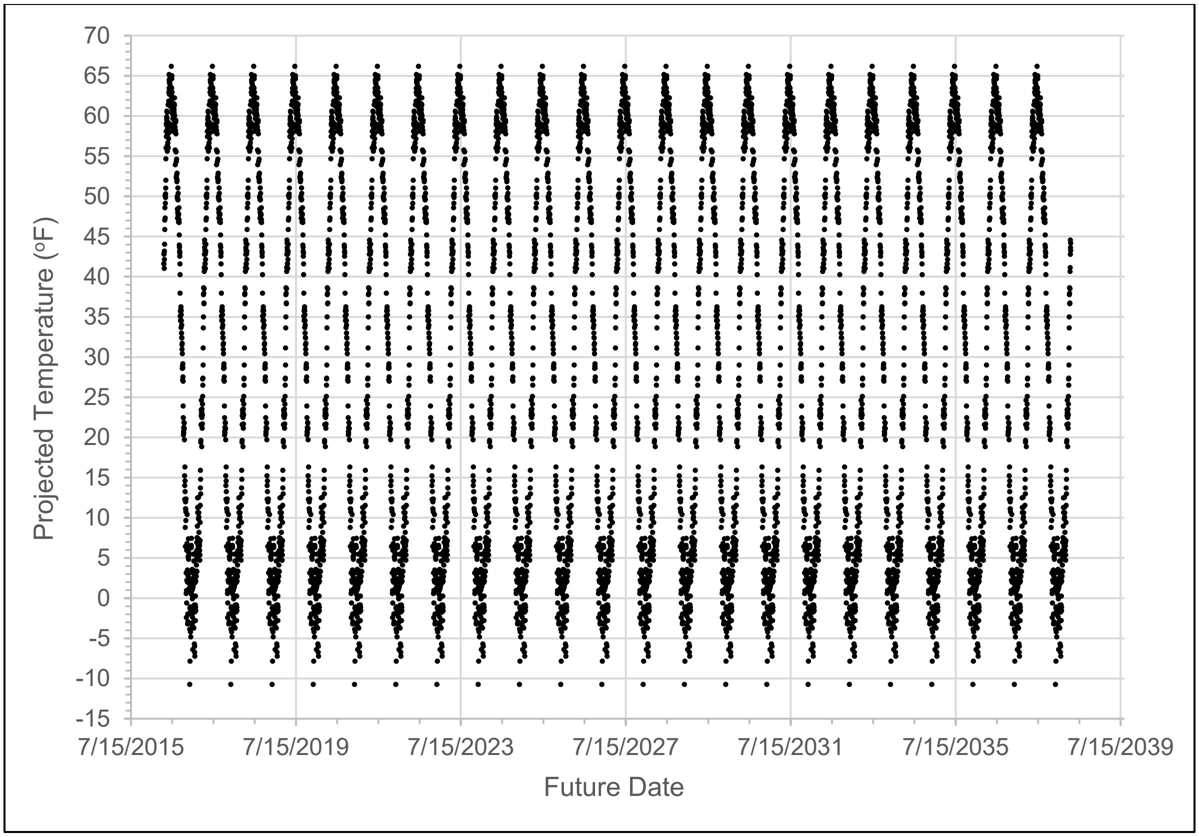


Figure 22. Estimated future air temperature profile for 2050, repeated 5/1/2016 – 4/30/2038.

We assumed that the load of the working platform and the subsequently constructed road embankment would compress the organic layers and near-surface silty soil within the active layer. Our model assumed this would result in roughly 12 inches of the 18 inch-thick working platform sinking below the original ground surface with the bottom 9-inches being partially saturated. In addition to the soils included in the in-situ models, our embankment models incorporated embankment gravel, insulation board, compressed organic material and compressed silt. Figure 23 illustrates an example of the Temp/W output for a 5-foot-thick embankment with 2:1 shoulder slopes, insulation board and a stabilization berm. This thermal model output was for October 8, 2037; near the annual maximum depth of thaw, (dimensions are in feet and the 32-degree isotherm is labelled).

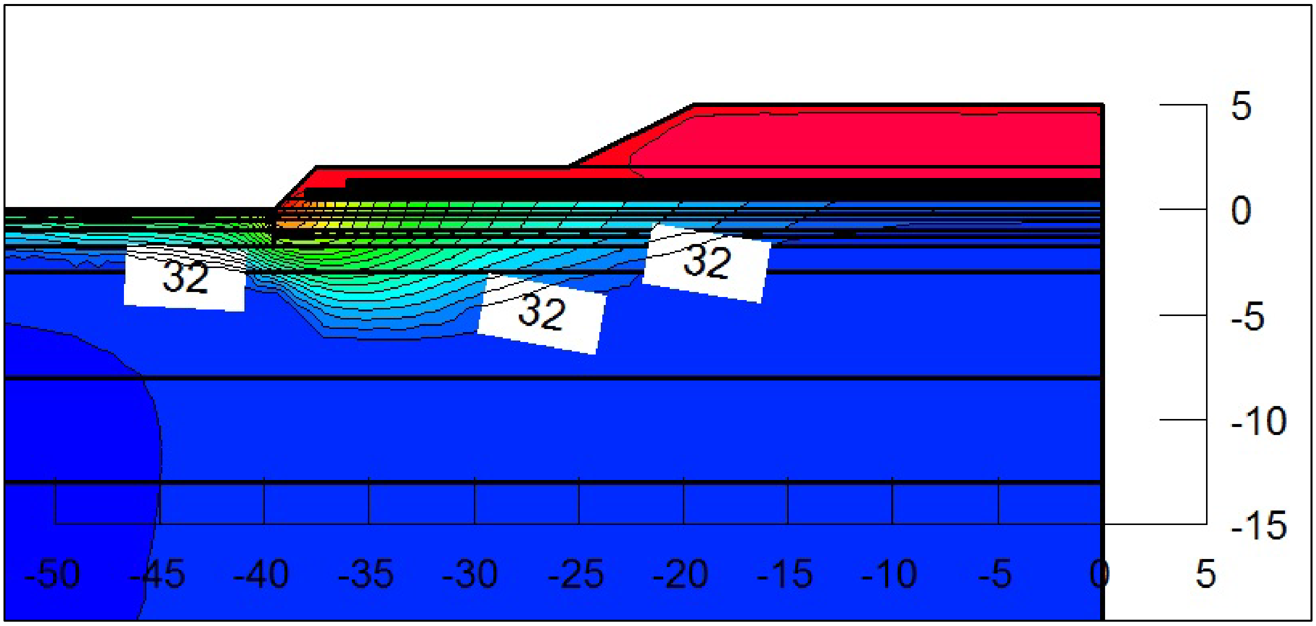


Figure 23. Temp/W output for 5-foot embankment with insulation and stabilization berm.

Although modeled embankment geometries varied, the sequence of soils beneath each one was the same. The following list summarizes, from embankment surface, our sequence of soils:

- **Gravel Embankment** of varied thickness containing varying thicknesses of insulation board. Twelve inches of this gravel embankment is assumed to settle below original grade.
- Nine of the 12 inches; lying below original grade; are considered **Wet Gravel Embankment**.
- The original 12-inch-thick sequence of live tundra, dead tundra and silty peat (see Table 8) is assumed to become three inches of **Compressed Organic Material.** The bottom of this layer lies 15 inches below original grade.
- 6 inches of **Compressed Silt**, the bottom of which lies 21 inches below original grade.
- Soils below this depth are the same as those in the in-situ model

We estimated the thermal properties of the above material types using the same methods used for the soils in the in-situ (pre-embankment) thermal model. These methods are described in the section titled "Subsurface Profile and Soil Thermal Properties" and Appendix A. Table 9 summarizes the thermal properties of the materials added to our embankment models.

The embankment models required surface boundary conditions for the embankment surface, embankment side-slope, and cleared tundra along the embankment margins. These boundary conditions were assumed for the embankment surface and side-slopes based on commonly accepted n-factor values and were calculated for the cleared tundra based on field measurements for Slightly Disturbed Tundra (see the discussion on “Surface Boundary Condition and Development of n-factors”). Table 10 summarizes the n-factors exclusive to the embankment models.

In the thermal modeling of the Dalton Highway MP 0-9 Realignment Project, the Soil Profile after Road Construction was used to model the depth of thaw under the “No-Settlement Assumption”; under this simplifying assumption, the Soil Profile after Road Construction was not modified each year to account for thaw-settlement. It is believed that this assumption will under-predict thaw depths for the various embankment configurations due to the model having reduced embankment thickness, lower moisture content and increased thermal conductivity in consolidated soils as compared to expected field conditions.

Table 9 - Summary of Embankment Model Thermal Properties

Material	Thickness (ft)	Dry-unit Weight (γ, lb/ft^3)	Organic Content (%)	Moisture		Thermal conductivity (Btu/ft-day-°F)		Heat capacity (Btu/ft^3-°F)	
				Gravimetric w%	Volumetric %	k_u	k_f	C_u	C_f
Embankment	varies	130	0	4.5	9.0	30.3	31.3	27.9	25.0
Wet Embankment	0.75	116	0	13.5	25.0	30.0	42.0	35.4	27.6
Insulation Board	varies	---	---	---	1.0	0.42	0.46	3.8	3.0
Compressed Organic Mat	0.25	56	76.4	42.3	38.0	5.2	6.9	47.4	36.3
Compressed Silt	0.5	61.8	20.1	48.5	48.0	11.1	20.2	44.6	31.2
Note: Many values estimated									

Table 10 - n-factors For Ground Surfaces in Embankment Models

Surface	**n_{thaw}**	**n_{freeze}**
Embankment - Gravel Surface	1.5	0.9
Embankment - Gravel Side-Slope	1.5	0.6
Cleared Tundra	0.92	0.47

Model Results

We used the model results to develop geotechnical recommendations for embankment design for the Dalton MP 0-9 Reconstruction project. To do this we assumed the thaw-depth results of each modeled embankment configuration generally applied along the length of the alignment and did not vary significantly due to varying subgrade conditions. Using this assumption, we estimated the thaw-settlement for six embankment configurations at each test hole drilled along the length of the alignment. This thaw-settlement at each test hole was calculated via spreadsheet in accordance to the underlying soils, their estimated consolidation properties, and distribution of embankment load with depth.

Total settlement and differential settlement both contribute to road maintenance requirements. Our analysis, therefore, not only reviewed total settlement at the embankment hinge point, but also reviewed differential settlement between the embankment's centerline and shoulder hinge point, as well as between the embankment's hinge point and the edge of the structural core of the embankment. As an example, Figure 24 illustrates the modeled thaw-depths beneath a 5-foot thick embankment with 2:1 side-slope and a stabilization berm with varying insulation thicknesses. Table 11- Thaw Depth and Settlement For 5-foot, 2H:1V Embankment summarizes the estimated thaw and settlement under the selected portions of this embankment. The additional examples for all of the embankments analyzed are illustrated in Appendix B.

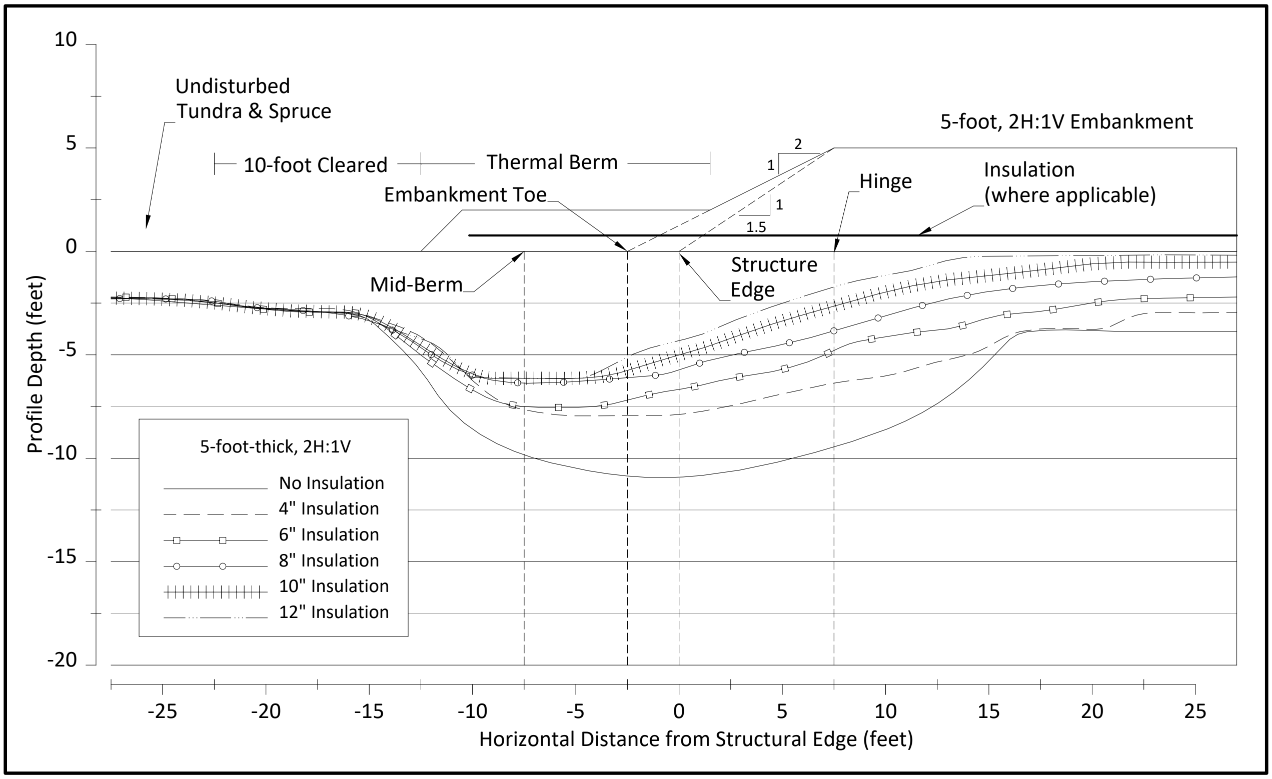


Figure 24. Model thaw depth beneath the 5-foot-thick embankment with 2:1 shoulder, slope and stabilization berm.

Table 11- Thaw Depth and Settlement For 5-foot, 2H:1V Embankment

Point		**Insulation Configuration**					
		0 - inches	**4 - inches**	**6 - inches**	**8 - inches**	**10 - inches**	**12 - inches**
Center	Thaw (ft.)	3.9	2.9	2.2	1.2	0.5	0.2
	Settlement (ft.)	**1.0**	**0.5**	**0.5**	**0.0**	**0.0**	**0.0**
Hinge	Thaw (ft.)	9.5	6.4	4.8	3.9	2.6	1.7
	Settlement (ft.)	**3.5**	**2.5**	**1.5**	**1.0**	**0.5**	**0.0**
Structure Edge	Thaw (ft.)	10.9	7.9	6.7	5.7	5.0	4.3
	Settlement (ft.)	**3.5**	**3.0**	**2.5**	**2.0**	**1.5**	**1.0**
Embankment Toe	Thaw (ft.)	10.9	7.9	7.2	6.1	5.8	5.1
	Settlement (ft.)	3.5	3.0	2.5	2.0	2.0	1.5

For each test hole location, the performance of the analyzed embankments were rated on a pass\fail system based upon both total and differential settlement criteria. Table 12 summarizes the pass\fail settlement criteria for each analyzed embankment configuration.

Table 12- Summary of Settlement Criteria for Modeled Embankment Configurations

Embankment			**Criteria for Passing**		
			Total Settlement (ft)	**Differential Settlement (ft)**	
Height (ft)	**Shoulder Slope (H:V)**	**Stabilization Berm (Y/N)**	**Embankment Hinge**	**Centerline to Hinge**	**Hinge to Structural Edge**
5	3:1	No	2	1.5	1
5	3:1	Yes	2	1.5	1
8	2:1	No	2	1.5	2
8	3:1	No	2	1.5	2
8	2:1	Yes	2	1.5	2
8	3:1	Yes	2	1.5	2

In general, along the length of the proposed alignment, we recommended embankments that did not exceed our allowed project settlement limits. We recommended Air Convection Embankments (ACE) along portions of the alignment where none of the analyzed road embankments passed our settlement analysis criteria.

Modeling ACE Embankment with AIR/W

GeoStudio AIR/W is a finite element computer software program that, when coupled with TEMP/W, is reportedly capable of modeling convective heat transfer. As part of this GAM Research Project, we initially intended on developing a method for modeling Air Convection Embankments (ACE) with the combination of these two software programs.

During this research, we acquired a complimentary temporary AIR/W license to combine with our TEMP/W software in order to develop convective thermal models for ACE embankments and shoulder treatments. While developing a convective thermal model with the combined AIR/W and TEMP/W software, we encountered a boundary condition problem. When AIR/W and TEMP/W are coupled, both a temperature and an air pressure boundary condition are required at each boundary surface. Any surface lacking a temperature boundary condition will be considered a zero-heat-flux surface by the software program. Similarly, any surface lacking an air pressure boundary condition will be considered a zero-air-flux surface by the program. If the entire perimeter of an ACE embankment was impermeable, a zero-air-flux condition would exist at its surfaces and the model should work. Although this may be the case under the asphalt, it is not the case along the outside margins of the ACE shoulders. Figure 25 illustrates a simple AIR/W model of a conventional, insulated core embankment with an ACE Shoulder. In this example, the top and sides of the ACE shoulder are open, porous, and allow both heat- and air-fluxes. These values, however, are unknown and are generally a measure of how well the ACE shoulder is stripping heat from the subgrade and embankment core. Therefore, it would be desirable for a model to determine these values, rather than requiring them as a user-defined boundary condition.

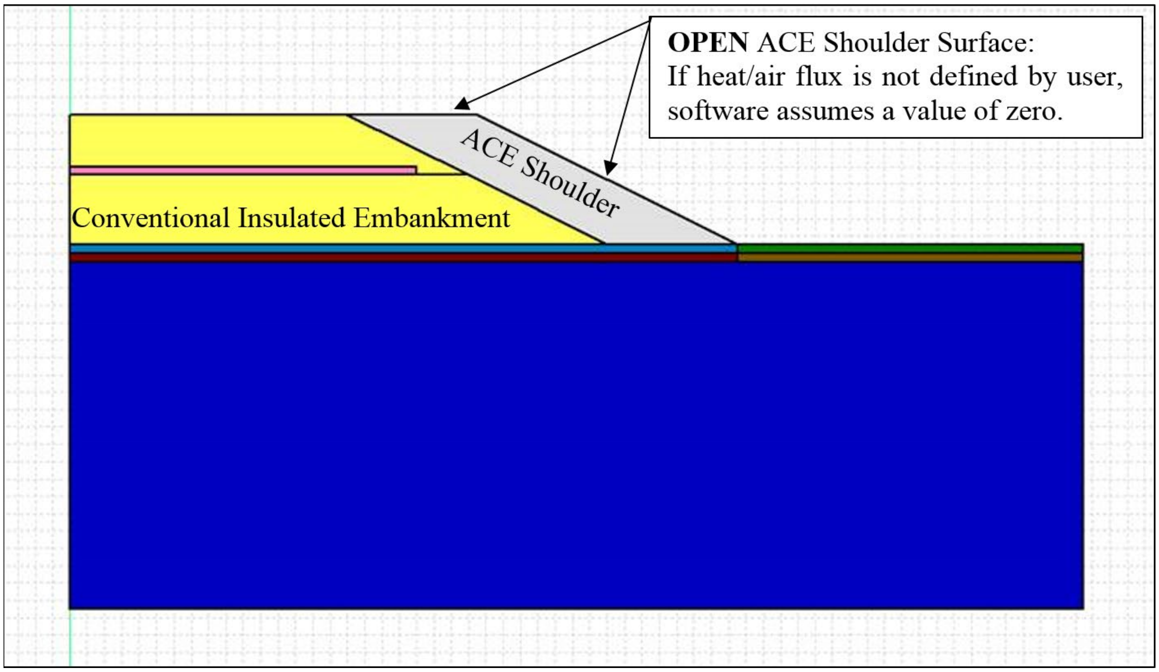


Figure 25. ACE Shoulder Embankment, Illustrating Flux-Surfaces

Our original intent was to employ the AIR/W and TEMP/W software to model the convective heat flow through the embankment based on temperature data from the project. We assumed the software would generate the air-flux along the ACE boundaries based on the model's thermal regime. The software however appears to require the user to define both the heat-flux and the air-flux along ACE shoulder edges.

Although originally included in the GAM Research Project budget, we have not purchased an AIR/W license, because we have yet to determine if AIR/W combined with TEMP/W is capable of modeling ACE embankments with open shoulders.

A research project was recently awarded to Dr. Doug Goering of the Alaska University Transportation Center, University of Alaska Fairbanks for Improved Permafrost Protection Using Air Convection and Ventilated Shoulder Cooling System. This research will focus on two specific objectives:

1. Better understand the performance of existing experimental features. The data available from the Thompson Drive experimental installation will be analyzed in order to accurately characterize the cooling effectiveness of the ACE, ventilated shoulder, and hairpin thermosiphon cooling features. Given the fourteen year temperature history available, analysis of this data set will allow accurate understanding of the long-term effectiveness of the installed cooling measures. The Thompson Drive data analysis will be augmented with data available from other projects, including the Alaska Highway MP 1354–1364 Experimental Feature, the Dalton Highway MP 209-222 Experimental Feature and the Elliot Highway MP 0-12 Experimental Feature as that additional data becomes available.

2. Improve our ability to design and simulate ACE embankments and ACE/ventilated shoulders. Using the data analysis from objective 1, model verification studies will be undertaken using Geoslope TEMP/W and AIR/W or other appropriate modeling software. Once verified, additional modeling will be conducted to investigate varying design features and a suite of design recommendations will be developed in conjunction with the Technical Advisory Committee. This portion of the work will be aimed at providing improved design tools and recommendations that can be implemented and utilized by Alaska DOT&PF design engineers when considering ACE features in new projects.

Given that construction of the Dalton Highway MP 0-9 Project has been delayed until 2021 or later and the approval of the above referenced research project, we recommend Phase II of Geotechnical Asset Management (GAM) Through Thermal Modeling and Post-Construction Thermal Monitoring of Highway Embankments for the Dalton Highway MP 0-9 be suspended. The need for it can be assessed once embankment design for the project is completed and the results of the experimental features and research project are evaluated.

Research Results, Changes to Alaska DOT&PF Thermal Modeling Procedures and Recommendations for Future Research

The research efforts provided the following results and conclusions:

- The thermal model developed for the pre-embankment conditions corresponded well with measured ground temperatures and measured thaw depth.

- Air temperature varied over relatively short distances:
    - Air temperatures at Monitoring Station # 1 were generally 1 ºF colder than those recorded at the Livengood Airport Weather Station.
    - Air temperatures at Monitoring Station # 2 were generally 2 ºF colder than those recorded at the Livengood Airport Weather Station.
    - Air temperatures at Monitoring Station # 3 were generally 3 ºF colder than those recorded at the Livengood Airport Weather Station.

- There was little difference in thaw depth measured between undisturbed areas and locations of winter-only equipment travel; however, there was a doubling of the thaw depth between undisturbed areas and the locations of summer equipment travel / drilling operations.

- Hand-dug exploration test pits allowed for characterization of the vegetative mat and near-surface soil layers through observation and measurement of the vegetative mat, observation of near-surface ground water conditions, and sampling / laboratory testing of the near-surface soil layers.

- Observation of near-surface ground water conditions in test pits provided a mechanism for understanding the observed bi-annual "flat-lining" of near-surface ground temperatures. In the fall, near-surface ground temperatures were observed to remain at 32 °F for an extended period of time before they began to follow the trend of dropping air temperatures as the winter progressed. In the spring, they "flat-lined" again at 32 °F before following the upward trend of summer air temperatures.

- Measurement of near-surface ground temperatures allowed for calculation of seasonal n-factors for undisturbed vs. slightly disturbed tundra ground cover. These initial calculated n-factors were adjusted during thermal model calibration.

- There was good agreement between soil material thermal properties as estimated by the methods found in A Generalized Thermal Conductivity Model for Soils and Construction Materials – Côté & Konrad (2005) and traditional estimation methods used by Kersten and Johansen.

.

- Measured soil temperature at various depths allowed for adjustment of soil material thermal properties to calibrate the thermal model so that modeled cumulative thawing and freezing degree-days matched the measured cumulative thawing and freezing degree-days at depth.

- Measured temperature at the depth of no-annual temperature change allowed for determination of the lower boundary condition heat flux.

The research program and associated literature review has resulted in changes and refinements to Alaska DOT&PF's thermal modeling procedures as described in Appendix C, including the following:

- Site-specific air temperature records should be developed and compared to local longer-term records for development of historic temperature records for thermal modeling.

- Future air temperatures should be predicted by applying a temperature increase to a 365-day cycle. The temperature increase applied to the 365-day cycle should approximate that predicted by the SNAP (Scenarios Network for Alaska + Arctic Planning) RCP 6.0 mid-level emissions model. **(Note – Since completion of this research program, Northern Region of Alaska DOT&PF has determined that future air temperatures should be projected based upon SNAP (Scenarios Network for Alaska + Arctic Planning) RCP 8.5 high-level emissions model.)**

- Hand-dug exploration test pits should be done to characterize the vegetative mat and near-surface soil layers through observation and measurement of the vegetative mat, observation of near-surface ground water conditions, and sampling / laboratory testing of the near-surface soil layers. Estimates should be made as to the extent of compression and changes to thermal properties that each near-surface layer will undergo when loaded under a road embankment.

- Thermal models should include n-factors for "slightly disturbed" vegetation for the regions between the toe of road embankments and the edge of the clearing. Projects that include ice-rich soils should consider seasonal restrictions on clearing operations.

- An EXCEL spreadsheet was developed to facilitate rapid estimation of soil material thermal properties by the methods found in A Generalized Thermal Conductivity Model for Soils and Construction Materials – Côté & Konrad (2005) as described in Appendix A.

- Based on a literature review of research conducted on insulation board extracted from existing road embankments, the thermal properties for insulation board should be estimated for different moisture content levels depending upon the placement of the insulation board with respect to ground water. Thermal properties for insulation board placed in well-drained road embankments should be estimated assuming 1% (volumetric) moisture content. Thermal properties for insulation board placed in saturated conditions, such as under culverts, should be estimated assuming 6% (volumetric) moisture content.

- When project schedules allow for measurement of ground temperatures over a minimum of 1-year, the thermal model should be calibrated by adjusting the soil material thermal properties until modeled cumulative thawing and freezing degree-days match the measured cumulative thawing and freezing degree-days at depth.

- Site-specific ground temperatures should be used, when available, to determine the measured temperature at the depth of no-annual temperature change to allow for calibration of the model soil layer thermal properties and then the site specific heat flux.

  If the site-specific ground temperature record does not allow for determination of the measured temperature at the depth of no-annual temperature change, the Permafrost Laboratory web page at the UAF Geophysical Institute https://permafrost.gi.alaska.edu/sites_map should be reviewed to determine if there is ground temperature data within a reasonable distance from the project site that can be used to estimate the depth of no-annual temperature change or to calculate an area heat flux.

If the site-specific ground temperature record does not allow for determination of the measured temperature at the depth of no-annual temperature change and there is no other ground temperature data within a reasonable distance of the project site, the heat flux should be estimated using the 2015 Heat Flow Map of Alaska. Caution should be used with this data to reduce the chances of using an artificially high heat flux; particularly near mineralized areas that commonly have relatively high local geothermal gradients.

Recommendations for future research include:

- If the Dalton Highway MP 0-9 Project is constructed, we recommend measuring ground temperatures under the constructed embankment to allow for evaluation of assumed compression of the vegetative mat and near-surface soil layers and changes to their original thermal properties.

- Collaboration with Dr. Doug Goering of the Alaska University Transportation Center, University of Alaska Fairbanks on the Improved Permafrost Protection Using Air Convection and Ventilated Shoulder Cooling System research program to:

    - Better understand the performance of existing ACE Embankments and shoulders.
    - Improve our ability to model, design and simulate ACE embankments and ACE/ventilated shoulders.
    - Investigate varying ACE design features and develop design recommendations aimed at optimizing design and minimizing life-cycle costs for ACE features that can be implemented and utilized by Alaska DOT&PF design engineers when considering ACE features in new projects.

- Obtain a needle-probe for measurement of soil thermal conductivity and develop practice and procedures for incorporation of this testing into geotechnical investigations. Organic soils from test pits and boreholes should be brought back to NRMS for determination of frozen and unfrozen thermal conductivity at varying moisture contents for the development of a database.

- Collaboration with Dr. Margaret Darrow of the University of Alaska Fairbanks on the measurement of unfrozen moisture content of frozen soil samples obtained from geotechnical investigations and the development of a database of unfrozen moisture content for Alaskan soils.

References

Côté, J., and Konrad, J-M. 2005. A generalized thermal conductivity model for soils and construction materials. Canadian Geotechnical Journal, 42: 443-458

Darrow, M. 2010. Measurement of Temperature and Soil Properties for Finite Element Model Verification. Alaska Department of Transportation and Public Facilities, Alaska University Transportation Center, University of Alaska Institute of Northern Engineering.

Farouki, O. 1981. Thermal properties of Soils. United States Army Corps of Engineers Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire. CRREL Monograph 81-1, pp. 151

Hattie, R. and Goering, D. 2009. Air Convecting Embankment (ACE) Design Guide. Alaska Department of Transportation and Public Facilities

Johansen, O. 1975. Thermal Conductivity of Soils. Ph.D. thesis, University of Trondheim, Trondheim, Norway. Unites States Army Corps of Engineers Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire. CRREL Draft English Translation 637

Kersten , M. 1949. Thermal Properties of Soils. University of Minnesota Institute of Technology Engineering Experiment Station. Vol. LII, No. 21

Shur, Y., Kanevskiy, M., Dillon, M., Stephani, E., and O'Donnell, J. 2010. Geo Technical Investigations for the Dalton Highway Innovation Project As A Case Study of the Ice-Rich Syngenetic Permafrost. University Transportation Center, University of Alaska Institute of Northern Engineering and Alaska Department of Transportation and Public Facilities.

Appendix A

Soil Material Thermal Properties as Estimated per Method by Côté and Konrad (2005)

A spreadsheet was developed to estimate soil thermal conductivity in accordance to methods described by Côté and Konrad (2005). This spreadsheet allows the user to make assumptions of a soil's unfrozen moisture content, which is used in the spreadsheet's calculations but also modified appropriately for export into Temp/W.

This spreadsheet has been subdivided into four general sections. The first three are basic steps to execute calculations of thermal conductively in accordance to Côté and Konrad (2005). The fourth section of the spreadsheet calculates volumetric heat capacity. The following subsections detail the function of the portions of the spreadsheet that execute the calculations of thermal conductivity.

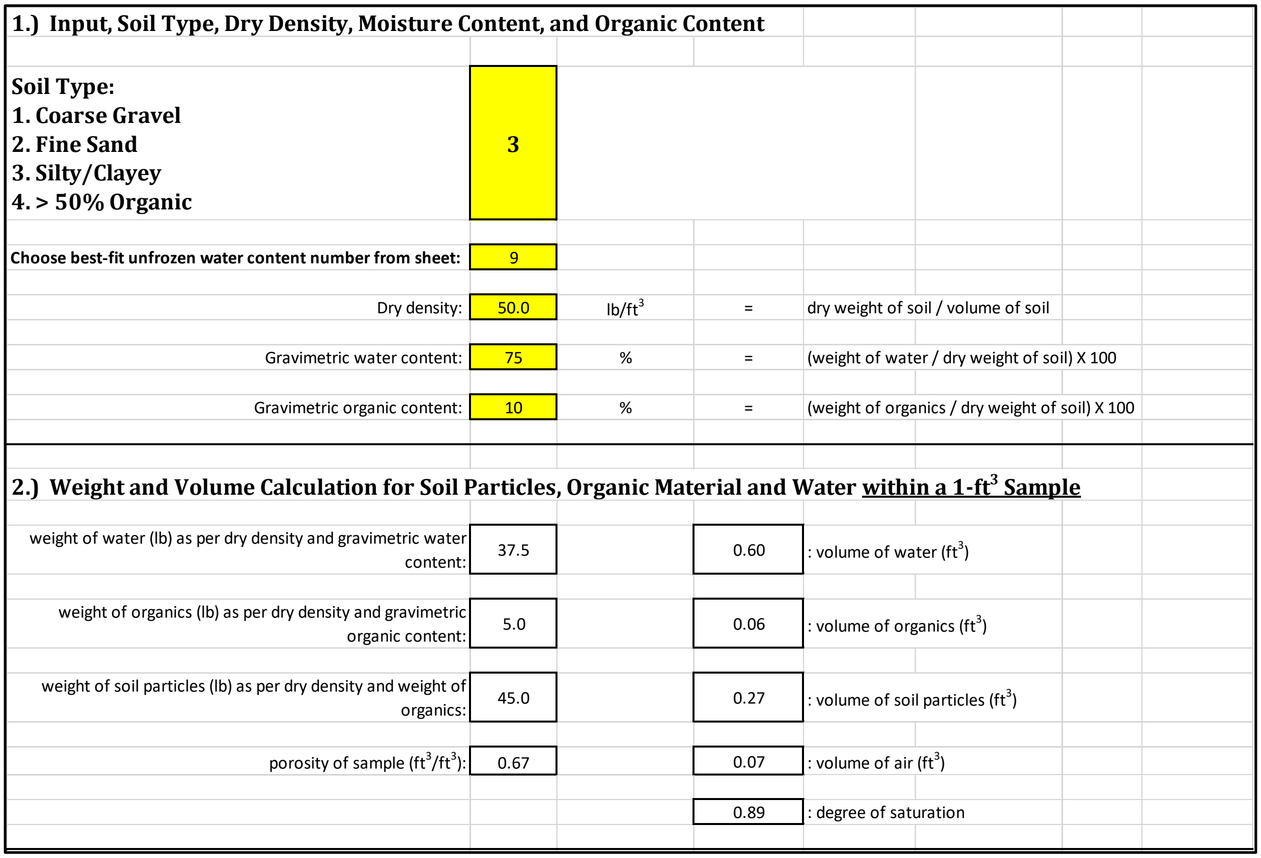
Steps 1 and 2: Input and Weight and Volume Relationships

These portions of the spreadsheet (see Figure A 1) calculate the respective weight and volumes for portions of a hypothetical 1-ft^3 sample containing soil, organic matter, water and air. These values are used for other various calculations within the spreadsheet.

The first input, "Soil Type", is used to calculate dry and normalized thermal conductivities (k_{dry}, k_r) in sections 3.3 and 3.4 of the spreadsheet. This input, therefore, should be the best match to the soil of which the user wishes to calculate thermal properties.

The second input, "choose best-fit unfrozen water content number from sheet" references an array of unfrozen moisture content curves acquired from several sources and placed in a separate sheet labelled "unfrozen water content" (see Figure A 2). This input requires the user to enter the number placed above the most appropriate unfrozen moisture curve within the "unfrozen water content" tab into cell B5. The chosen unfrozen moisture content curve is used to calculate temperature dependent thermal conductivity of the sample when saturated (k_{sat}), which, in part, is used to calculate the temperature dependent thermal conductivity of soil at in-situ moisture-content.

The input for dry density, gravimetric water content and gravimetric organic content are used to calculate both the weight and volume portions of soil, organic matter, H_2O, and air in a ft^3 sample of the respective soil. These values are used for multiple calculations throughout the spreadsheet.



1.) Input, Soil Type, Dry Density, Moisture Content, and Organic Content

Soil Type:
1. Coarse Gravel
2. Fine Sand
3. Silty/Clayey
4. > 50% Organic

3

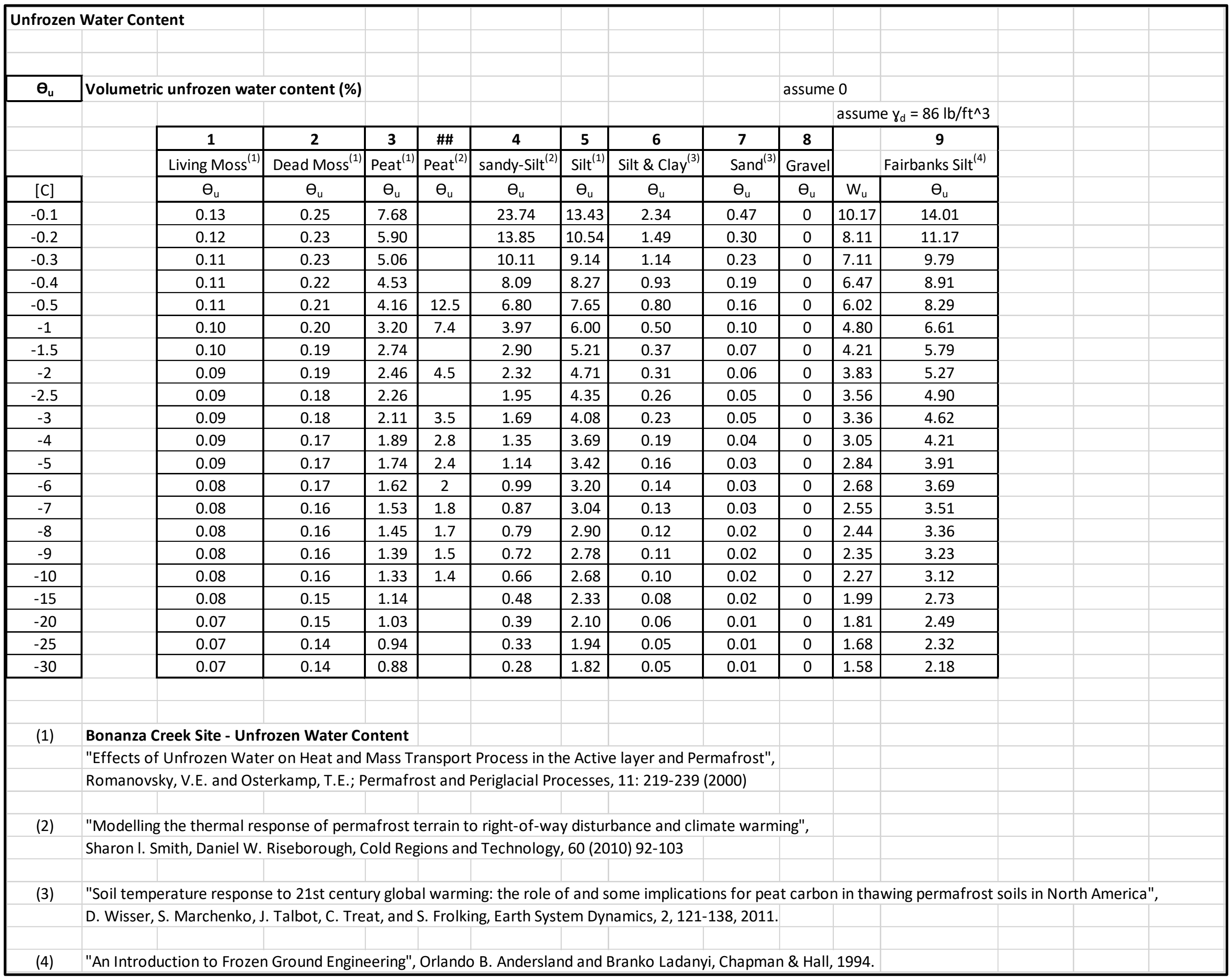
Choose best-fit unfrozen water content number from sheet: 9

Dry density:	50.0	lb/ft^3	=	dry weight of soil / volume of soil
Gravimetric water content:	75	%	=	(weight of water / dry weight of soil) X 100
Gravimetric organic content:	10	%	=	(weight of organics / dry weight of soil) X 100

2.) Weight and Volume Calculation for Soil Particles, Organic Material and Water within a 1-ft^3 Sample

weight of water (lb) as per dry density and gravimetric water content:	37.5	0.60	: volume of water (ft^3)
weight of organics (lb) as per dry density and gravimetric organic content:	5.0	0.06	: volume of organics (ft^3)
weight of soil particles (lb) as per dry density and weight of organics:	45.0	0.27	: volume of soil particles (ft^3)
porosity of sample (ft^3/ft^3):	0.67	0.07	: volume of air (ft^3)
		0.89	: degree of saturation

Figure A-1: Sections 1 and 2 of the Thermal Property Spreadsheet



Unfrozen Water Content

Θ_u	**Volumetric unfrozen water content (%)**

assume 0

assume γ_d = 86 lb/ft^3

	1	**2**	**3**	**##**	**4**	**5**	**6**	**7**	**8**		**9**
	Living Moss$^{(1)}$	Dead Moss$^{(1)}$	Peat$^{(1)}$	Peat$^{(2)}$	sandy-Silt$^{(2)}$	Silt$^{(1)}$	Silt & Clay$^{(3)}$	Sand$^{(3)}$	Gravel		Fairbanks Silt$^{(4)}$
[C]	Θ_u	Θ_u	Θ_u	Θ_u	Θ_u	Θ_u	Θ_u	Θ_u	Θ_u	W_u	Θ_u
-0.1	0.13	0.25	7.68		23.74	13.43	2.34	0.47	0	10.17	14.01
-0.2	0.12	0.23	5.90		13.85	10.54	1.49	0.30	0	8.11	11.17
-0.3	0.11	0.23	5.06		10.11	9.14	1.14	0.23	0	7.11	9.79
-0.4	0.11	0.22	4.53		8.09	8.27	0.93	0.19	0	6.47	8.91
-0.5	0.11	0.21	4.16	12.5	6.80	7.65	0.80	0.16	0	6.02	8.29
-1	0.10	0.20	3.20	7.4	3.97	6.00	0.50	0.10	0	4.80	6.61
-1.5	0.10	0.19	2.74		2.90	5.21	0.37	0.07	0	4.21	5.79
-2	0.09	0.19	2.46	4.5	2.32	4.71	0.31	0.06	0	3.83	5.27
-2.5	0.09	0.18	2.26		1.95	4.35	0.26	0.05	0	3.56	4.90
-3	0.09	0.18	2.11	3.5	1.69	4.08	0.23	0.05	0	3.36	4.62
-4	0.09	0.17	1.89	2.8	1.35	3.69	0.19	0.04	0	3.05	4.21
-5	0.09	0.17	1.74	2.4	1.14	3.42	0.16	0.03	0	2.84	3.91
-6	0.08	0.17	1.62	2	0.99	3.20	0.14	0.03	0	2.68	3.69
-7	0.08	0.16	1.53	1.8	0.87	3.04	0.13	0.03	0	2.55	3.51
-8	0.08	0.16	1.45	1.7	0.79	2.90	0.12	0.02	0	2.44	3.36
-9	0.08	0.16	1.39	1.5	0.72	2.78	0.11	0.02	0	2.35	3.23
-10	0.08	0.16	1.33	1.4	0.66	2.68	0.10	0.02	0	2.27	3.12
-15	0.08	0.15	1.14		0.48	2.33	0.08	0.02	0	1.99	2.73
-20	0.07	0.15	1.03		0.39	2.10	0.06	0.01	0	1.81	2.49
-25	0.07	0.14	0.94		0.33	1.94	0.05	0.01	0	1.68	2.32
-30	0.07	0.14	0.88		0.28	1.82	0.05	0.01	0	1.58	2.18

(1) **Bonanza Creek Site - Unfrozen Water Content**
"Effects of Unfrozen Water on Heat and Mass Transport Process in the Active layer and Permafrost",
Romanovsky, V.E. and Osterkamp, T.E.; Permafrost and Periglacial Processes, 11: 219-239 (2000)

(2) "Modelling the thermal response of permafrost terrain to right-of-way disturbance and climate warming",
Sharon l. Smith, Daniel W. Riseborough, Cold Regions and Technology, 60 (2010) 92-103

(3) "Soil temperature response to 21st century global warming: the role of and some implications for peat carbon in thawing permafrost soils in North America",
D. Wisser, S. Marchenko, J. Talbot, C. Treat, and S. Frolking, Earth System Dynamics, 2, 121-138, 2011.

(4) "An Introduction to Frozen Ground Engineering", Orlando B. Andersland and Branko Ladanyi, Chapman & Hall, 1994.

Figure A-2: Unfrozen Water Content Spreadsheet

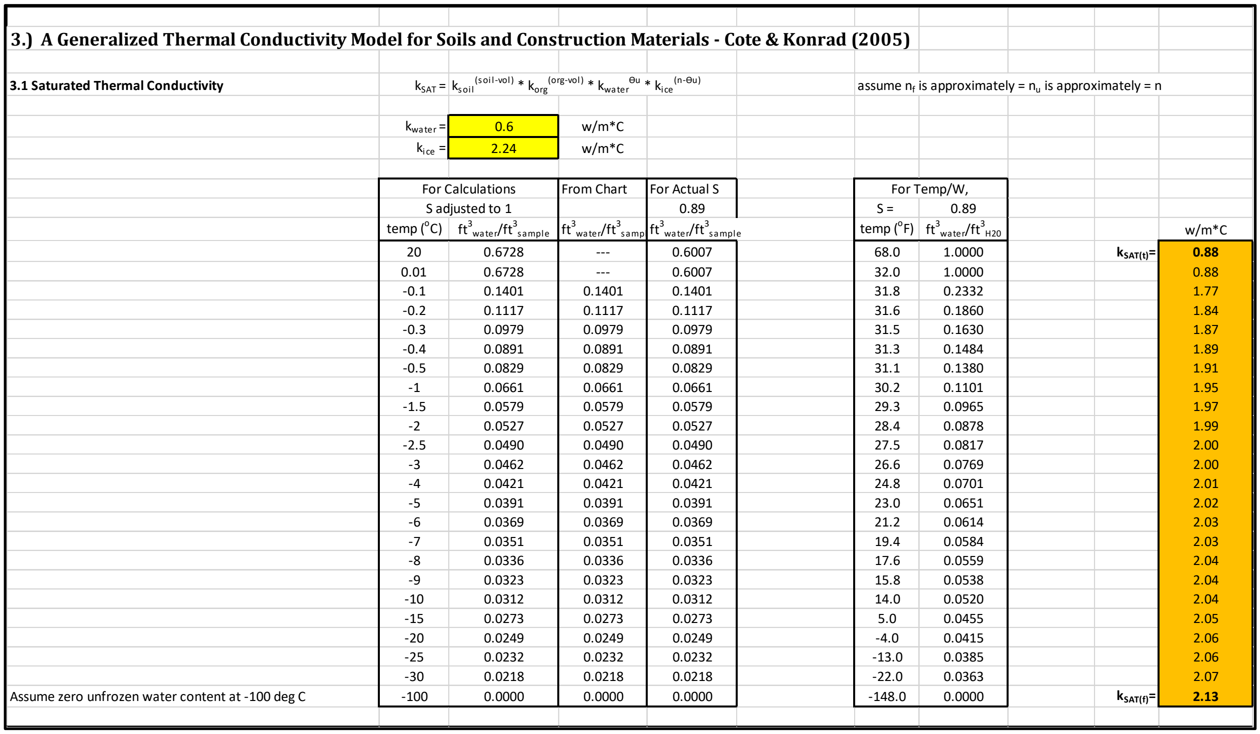
Step 3: Calculations in Accordance to Côté and Konrad (2005)

Once the soil type, weights and volumes, and the temperature-dependent unfrozen moisture-content are entered into the spreadsheet, thermal conductivity can be calculated. Figure A-3 illustrates section 3.1 of the spreadsheet which calculates the temperature dependent thermal conductivity of the input soil, assuming full saturation (k_{sat}), with the following equation:

$$k_{sat} = k_{soil}^{soil\ volume} \times k_{org}^{org\ volume} \times k_{water}^{water\ volume} \times k_{ice}^{ice\ volume}$$

Where the respective volumes add up to the total volume and are normalized to their portion of the total. This calculation is simply a geometric mean of the thermal conductivity and volume of each of the soils constituents. The respective volume of water and ice within the soil is a function of the soil's unfrozen water content at a given temperature.

It should be noted that if the soil is saturated in-situ, the Côté and Konrad (2005) equations for calculating its thermal conductivity reduce to this geometric mean equation (see discussion on section 3.3 of the spreadsheet).



3.) A Generalized Thermal Conductivity Model for Soils and Construction Materials - Cote & Konrad (2005)

3.1 Saturated Thermal Conductivity

$k_{SAT} = k_{soil}^{(soil\text{-}vol)} * k_{org}^{(org\text{-}vol)} * k_{water}^{\Theta u} * k_{ice}^{(n-\Theta u)}$

assume n_f is approximately = n_u is approximately = n

k_{water} = 0.6 w/m*C

k_{ice} = 2.24 w/m*C

	For Calculations		From Chart	For Actual S	For Temp/W,			
	S adjusted to 1			0.89	S =	0.89		
	temp (°C)	$ft^3_{water}/ft^3_{sample}$	ft^3_{water}/ft^3_{samp}	$ft^3_{water}/ft^3_{sample}$	temp (°F)	ft^3_{water}/ft^3_{H20}		w/m*C
	20	0.6728	---	0.6007	68.0	1.0000	**$k_{SAT(t)}$=**	**0.88**
	0.01	0.6728	---	0.6007	32.0	1.0000		0.88
	-0.1	0.1401	0.1401	0.1401	31.8	0.2332		1.77
	-0.2	0.1117	0.1117	0.1117	31.6	0.1860		1.84
	-0.3	0.0979	0.0979	0.0979	31.5	0.1630		1.87
	-0.4	0.0891	0.0891	0.0891	31.3	0.1484		1.89
	-0.5	0.0829	0.0829	0.0829	31.1	0.1380		1.91
	-1	0.0661	0.0661	0.0661	30.2	0.1101		1.95
	-1.5	0.0579	0.0579	0.0579	29.3	0.0965		1.97
	-2	0.0527	0.0527	0.0527	28.4	0.0878		1.99
	-2.5	0.0490	0.0490	0.0490	27.5	0.0817		2.00
	-3	0.0462	0.0462	0.0462	26.6	0.0769		2.00
	-4	0.0421	0.0421	0.0421	24.8	0.0701		2.01
	-5	0.0391	0.0391	0.0391	23.0	0.0651		2.02
	-6	0.0369	0.0369	0.0369	21.2	0.0614		2.03
	-7	0.0351	0.0351	0.0351	19.4	0.0584		2.03
	-8	0.0336	0.0336	0.0336	17.6	0.0559		2.04
	-9	0.0323	0.0323	0.0323	15.8	0.0538		2.04
	-10	0.0312	0.0312	0.0312	14.0	0.0520		2.04
	-15	0.0273	0.0273	0.0273	5.0	0.0455		2.05
	-20	0.0249	0.0249	0.0249	-4.0	0.0415		2.06
	-25	0.0232	0.0232	0.0232	-13.0	0.0385		2.06
	-30	0.0218	0.0218	0.0218	-22.0	0.0363		2.07
Assume zero unfrozen water content at -100 deg C	-100	0.0000	0.0000	0.0000	-148.0	0.0000	**$k_{SAT(f)}$=**	**2.13**

Figure A-3: Thermal Conductivity of Saturated Soil

Sections 3.2 and 3.3 (see Figure A-4) of the spreadsheet calculates the dry and normalized thermal conductivities. These values, in addition to the saturated thermal conductivity are used to determine the soil's thermal conductivity at its in-situ moisture-content.

According to the Côté and Konrad (2005) method, the dry thermal conductivity is a function of porosity (n) and two material parameters that account for particle shape. These two material properties are designated as χ, which is in W/m °C, and η, which is unitless. The dry thermal conductivity is calculated by the following equation:

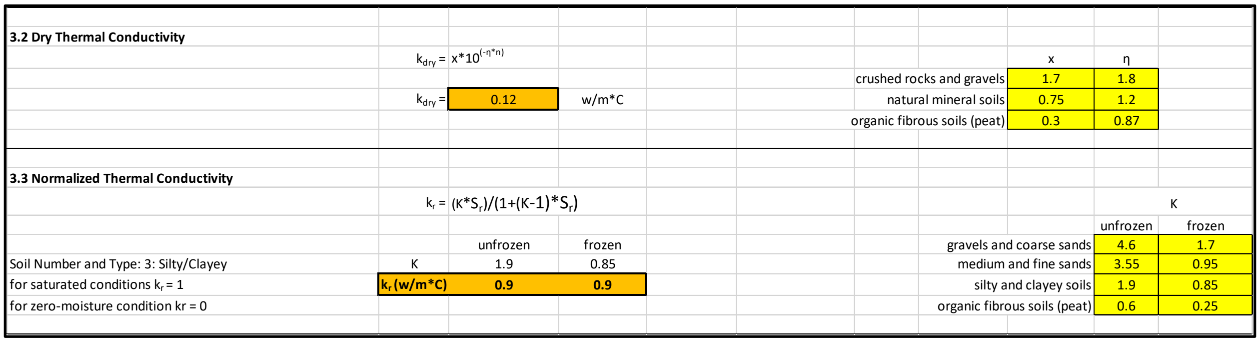
$$k_{dry} = \chi \times 10^{-\eta n}$$

A small table that illustrates these material parameters for crushed rocks and gravel, natural mineral soils, and peat has been provided in the right side of section 3.2. The spreadsheet automatically selects these parameters in accordance to the soil type.

The normalized thermal conductivity k_r, adjusts the calculated thermal conductivity in accordance to the soil's in-situ moisture content. According to the Côté and Konrad (2005) method, this variable is calculated by the following equation:

$$k_r = \frac{\kappa S_r}{1 + (\kappa - 1)S_r}$$

Where κ is an empirical parameter related to the soil type and S_r is the soil's degree of saturation. Note that when $S_r = 1$ this equation is simplified to $K_r = 1$. This in turn, reduces the Côté and Konrad (2005) equation for thermal conductivity to the saturated thermal conductivity, which is calculated from the geometric mean of the soils constituents and their respective volumes.



3.2 Dry Thermal Conductivity

k_{dry} = x*$10^{(-\eta*n)}$

k_{dry} = 0.12 w/m*C

	x	η
crushed rocks and gravels	1.7	1.8
natural mineral soils	0.75	1.2
organic fibrous soils (peat)	0.3	0.87

3.3 Normalized Thermal Conductivity

k_r = (K*S_r)/(1+(K-1)*S_r)

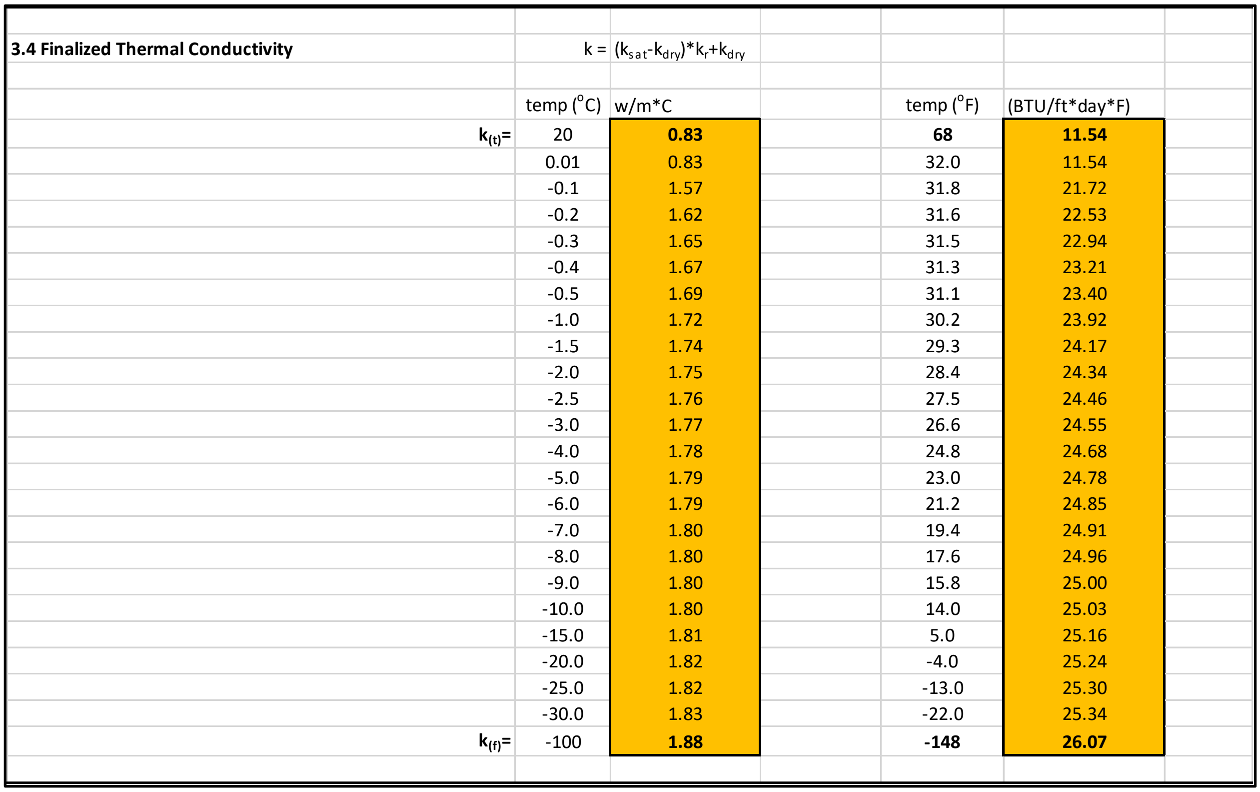
		unfrozen	frozen
Soil Number and Type: 3: Silty/Clayey	K	1.9	0.85
for saturated conditions k_r = 1	**k_r (w/m*C)**	**0.9**	**0.9**
for zero-moisture condition kr = 0			

	K unfrozen	K frozen
gravels and coarse sands	4.6	1.7
medium and fine sands	3.55	0.95
silty and clayey soils	1.9	0.85
organic fibrous soils (peat)	0.6	0.25

Figure A-4: Dry and Normalized Thermal Conductivities

Section 3.4 of the spreadsheet (see Figure A-5) calculates the temperature-dependent thermal conductivity of the soil based upon the soil's unfrozen moisture content, k_s, k_{dry}, and k_r These calculations are in accordance to the following equation developed Côté and Konrad (2005):

$$k = (k_{sat} - k_{dry})k_r + k_{dry}$$



3.4 Finalized Thermal Conductivity k = $(k_{sat}-k_{dry})*k_r+k_{dry}$

	temp (°C)	w/m*C	temp (°F)	(BTU/ft*day*F)
$k_{(t)}$=	20	**0.83**	**68**	**11.54**
	0.01	0.83	32.0	11.54
	-0.1	1.57	31.8	21.72
	-0.2	1.62	31.6	22.53
	-0.3	1.65	31.5	22.94
	-0.4	1.67	31.3	23.21
	-0.5	1.69	31.1	23.40
	-1.0	1.72	30.2	23.92
	-1.5	1.74	29.3	24.17
	-2.0	1.75	28.4	24.34
	-2.5	1.76	27.5	24.46
	-3.0	1.77	26.6	24.55
	-4.0	1.78	24.8	24.68
	-5.0	1.79	23.0	24.78
	-6.0	1.79	21.2	24.85
	-7.0	1.80	19.4	24.91
	-8.0	1.80	17.6	24.96
	-9.0	1.80	15.8	25.00
	-10.0	1.80	14.0	25.03
	-15.0	1.81	5.0	25.16
	-20.0	1.82	-4.0	25.24
	-25.0	1.82	-13.0	25.30
	-30.0	1.83	-22.0	25.34
$k_{(f)}$=	-100	**1.88**	**-148**	**26.07**

Figure A-5: Finalized Thermal Conductivity

Comparison of Thermal Conductivity Calculations

To compare our results with other conventional methods, we developed 48 hypothetical soils, calculated each soil's thawed and frozen thermal conductivity with our spreadsheet and either Kersten's (1949) or Johansen's (1975) methods, and compared the results. In addition, we entered the physical properties of nine soils reported by Darrow (2010), calculated their thermal properties by both our spreadsheet and Kersten's (1949) equations, and compared these two results to those reported.

Our 48 hypothetical soils covered an array of soil type, soil density and degree of water saturation. Sixteen of these soils were either sand or gravel, 12 were fine-grained, and 20 were peat. The thermal conductivities of these soils were calculated via our spreadsheet, and compared to calculations in accordance to the Kersten (1949) or Johansen (1975) method via the following equations:

Kersten (1949):

- Fine-grained soil

$$k_{thawed} = [0.9log(moisture\ content) - 0.2]10^{0.01\gamma_{dry}}$$

$$k_{frozen} = 0.01(10)^{0.022\gamma_{dry}} + (0.085(10)^{0.008\gamma_{dry}})\ X\ (moisture\ content)$$

- Sand and Gravel

$$k_{thawed} = [0.7log(moisture\ content) + 0.4]10^{0.01\gamma_{dry}}$$

$$k_{frozen} = 0.076(10)^{0.013\gamma_{dry}} + (0.032(10)^{0.0146\gamma_{dry}})\ X\ (moisture\ content)$$

Johansen (1975)

- Peat Soil

$$k_{thawed} = \left[S_r\left(\sqrt{k_{sat}} - \sqrt{k_{dry}}\right) + \sqrt{k_{dry}}\right]^2$$

$$k_{frozen} = k_{dry}\left(\frac{k_{sat}}{k_{dry}}\right)^2$$

Figure A-6 illustrates the comparison between calculated thermal conductivities of the 16 hypothetical granular soils of varying density and degree of water saturation. The values calculated via our spreadsheet are illustrated in the y-axis while the values calculated via the Kersten (1949) equations are illustrated in the x-axis.

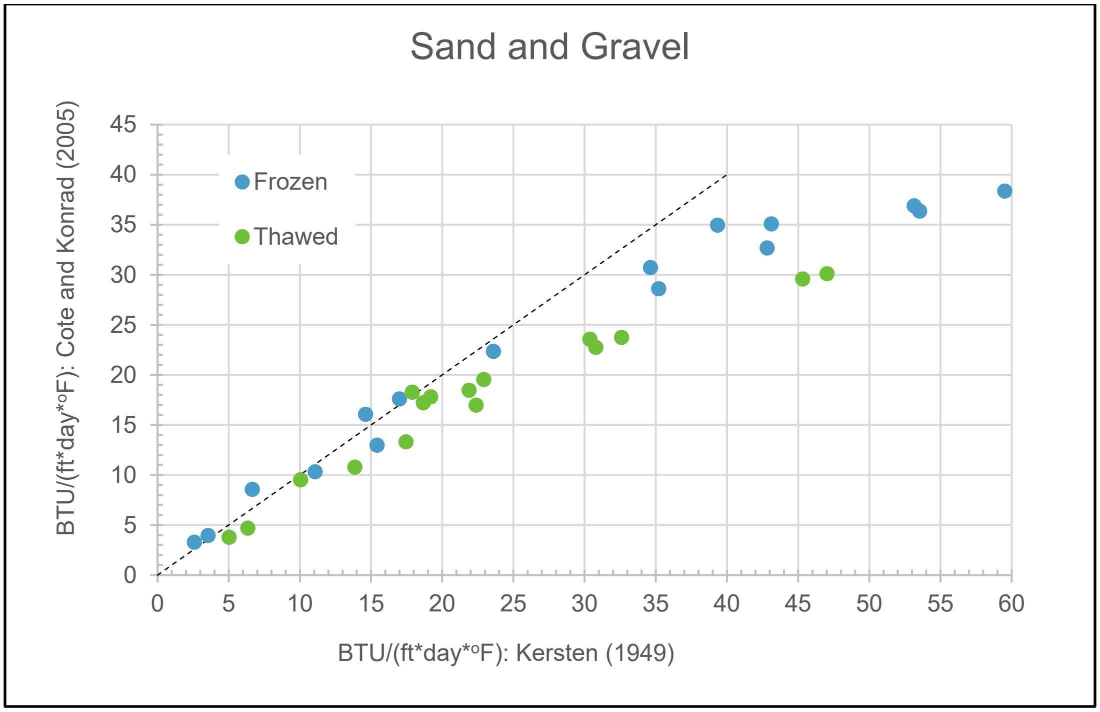


Figure A-6: Comparison between calculated thermal conductivities for granular soil.

Figure A-7 illustrates the comparison between calculated thermal conductivities of the 12 hypothetical fine-grained soils of varying density and degree of water saturation. The values calculated via our spreadsheet are illustrated in the y-axis while the values calculated via the Kersten (1949) equations are illustrated in the x-axis.

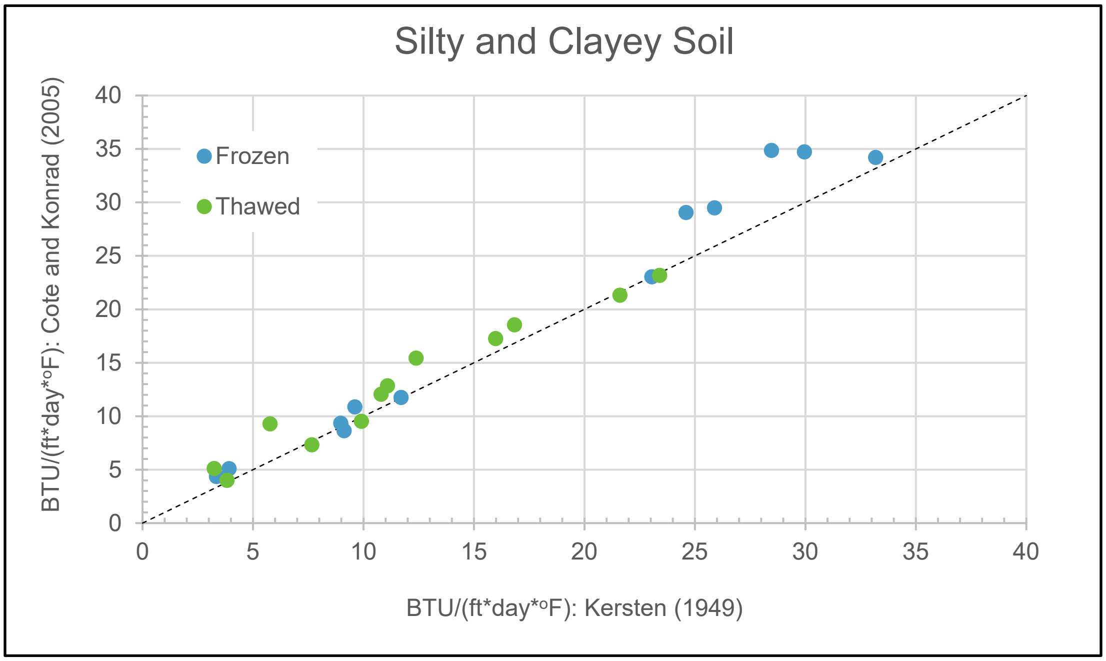


Figure A-7: Comparison between calculated thermal conductivities for fine-grained soil.

Figure A-8 illustrates the comparison between calculated thermal conductivities of the 20 hypothetical peat soils of varying density and degree of water saturation. The values calculated via our spreadsheet are illustrated in the y-axis while the values calculated via the Kersten (1949) equations are illustrated in the x-axis.

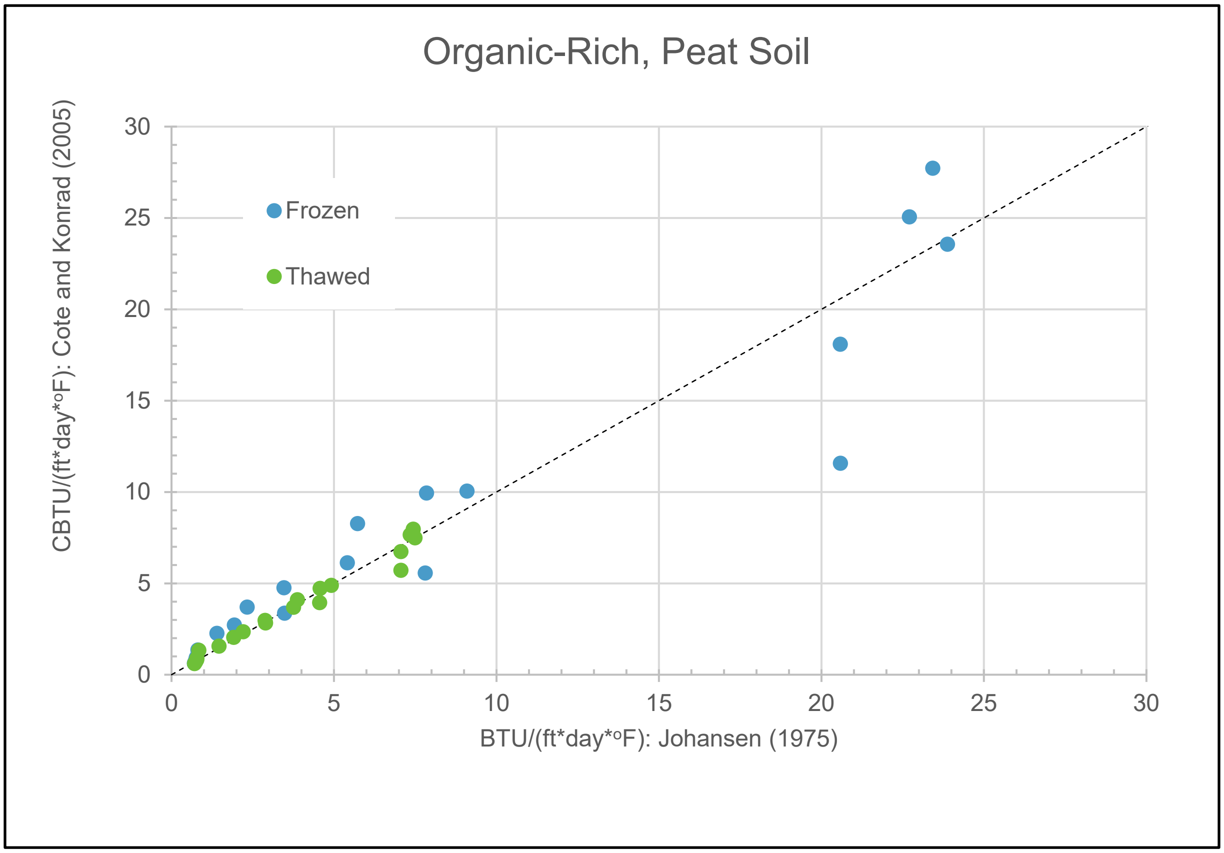


Figure A-8: Comparison between calculated thermal conductivities for peat.

Figures A-9 and A-10 illustrate the comparison between calculated thawed and frozen thermal conductivities of ten soils reported by Darrow (2010), respectively. The values illustrated for Cote and Konrad (2005) and the Kersten (1949) were calculated via our spreadsheet and Kersten's (1949) equations, respectively. The values illustrated for Darrow (2010) are those reported.

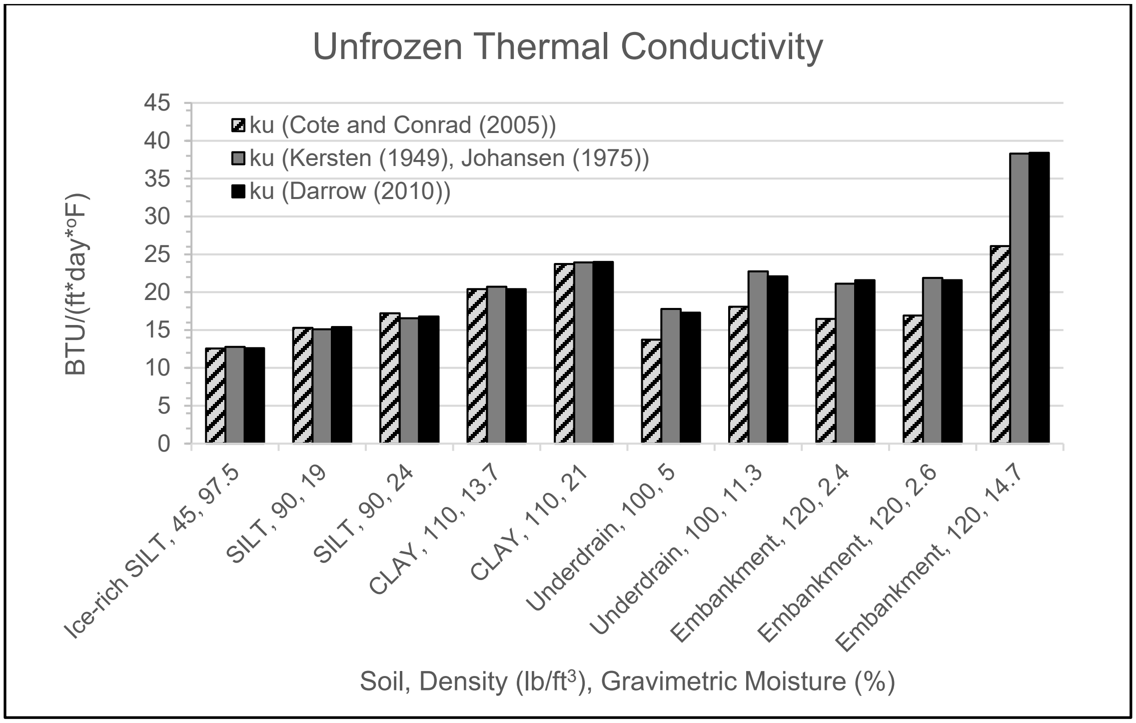


Figure A-9: comparison of calculated unfrozen thermal conductivities for soil reported by Darrow (2010).

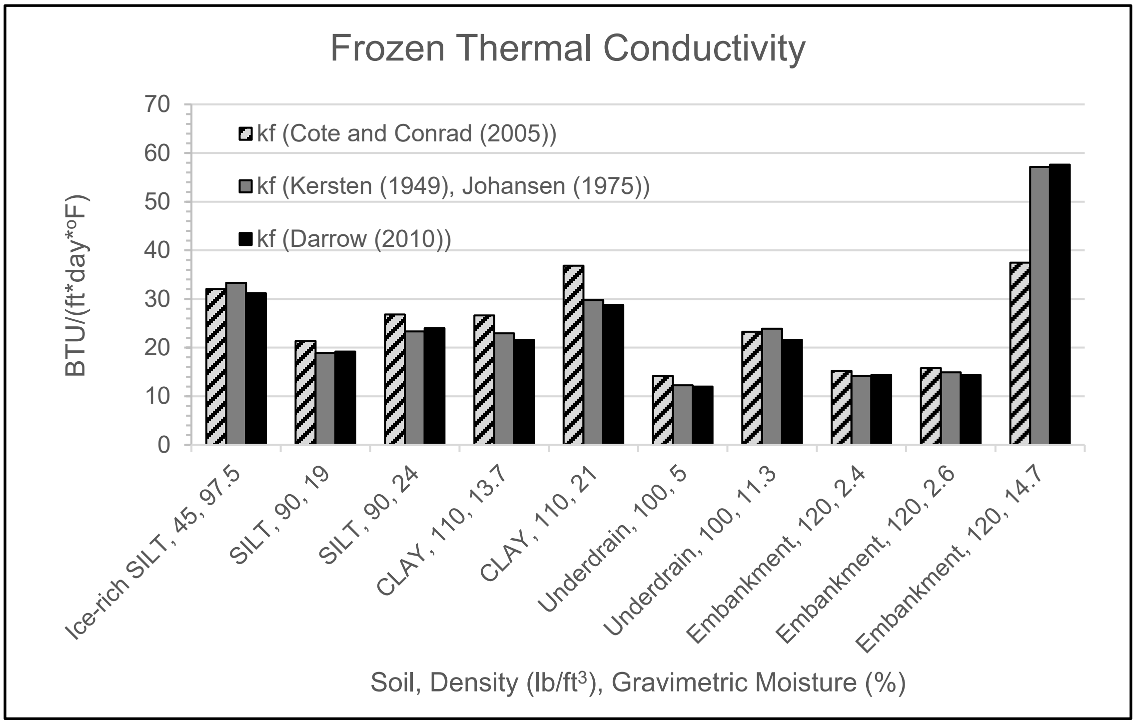


Figure A-10: Comparison of calculated frozen thermal conductivities for soil reported by Darrow (2010).

Appendix B

Modeled Thaw-Depths vs. Insulation Board Thickness
and
Estimated Settlement vs. Thaw Depth
for Various Road Embankments
Dalton Highway MP 0-9 Realignment

All models were run with a gravel-surface road embankment.

All models were run using projected 2049 air temperatures based on the SNAP (Scenarios Network for Alaska + Arctic Planning) RCP 6.0 mid-level emissions model.

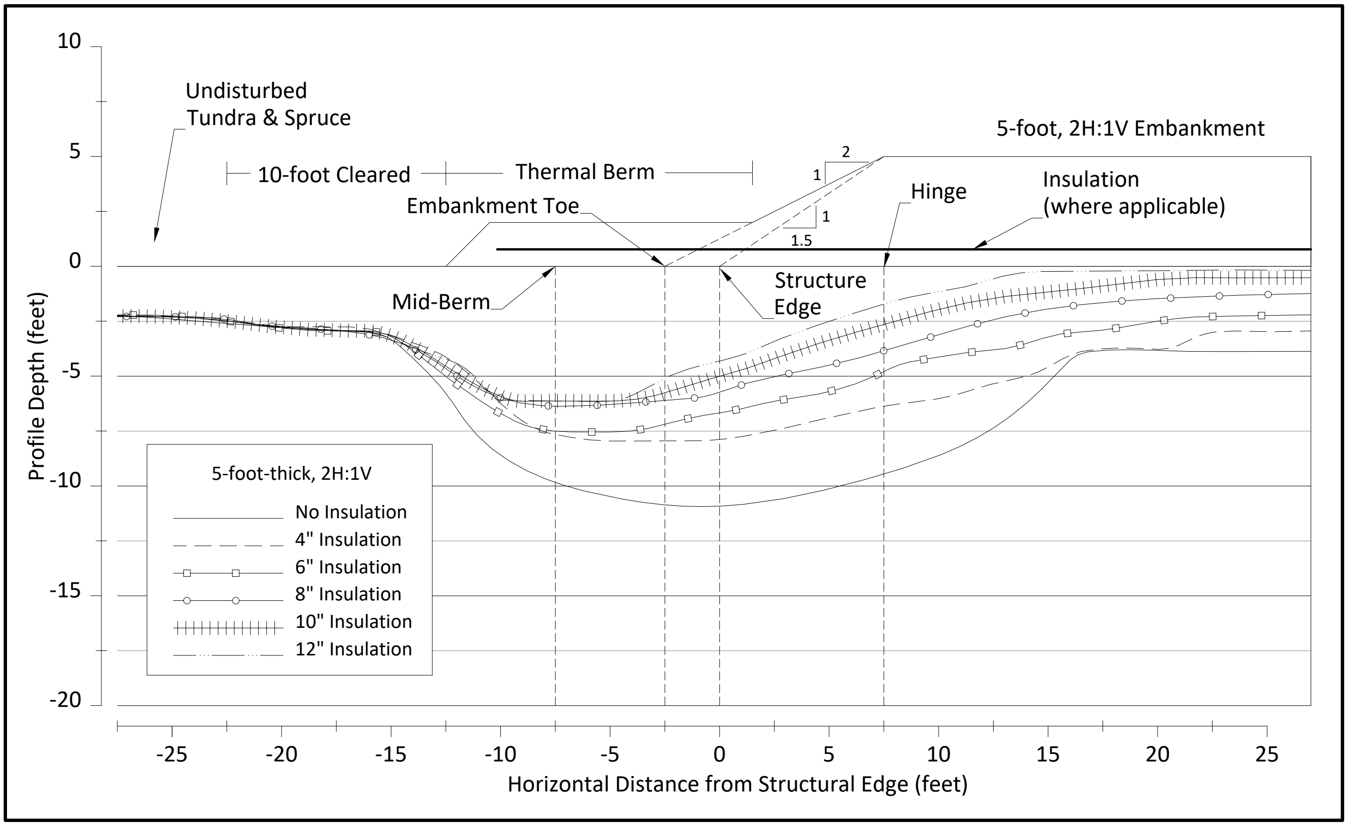


Figure B-1: Thaw Depth versus Insulation For 5-foot, 2H:1V Gravel-Surfaced Embankment
(2049, RCP6.0, mid-level emissions repeated for 19 years/18 thaw-seasons)

Table B-1: Thaw Depth versus Settlement For 5-foot, 2H:1V Gravel-Surfaced Embankment
(2049, RCP6.0, mid-level emissions repeated for 19 years/18 thaw-seasons)

Point		**Insulation Configuration**					
		NI	**4-inches**	**6-inches**	**8-inches**	**10-inches**	**12-inches**
Center	Thaw (ft.)	3.9	2.9	2.2	1.2	0.5	0.2
	Settlement (ft.)	**1.0**	**0.5**	**0.5**	**0.0**	**0.0**	**0.0**
Hinge	Thaw (ft.)	9.5	6.4	4.8	3.9	2.6	1.7
	Settlement (ft.)	**3.5**	**2.5**	**1.5**	**1.0**	**0.5**	**0.0**
Structure Edge	Thaw (ft.)	10.9	7.9	6.7	5.7	5.0	4.3
	Settlement (ft.)	**3.5**	**3.0**	**2.5**	**2.0**	**1.5**	**1.0**
Embankment Toe	Thaw (ft.)	10.9	7.9	7.2	6.1	5.8	5.1
	Settlement (ft.)	**3.5**	**3.0**	**2.5**	**2.0**	**2.0**	**1.5**

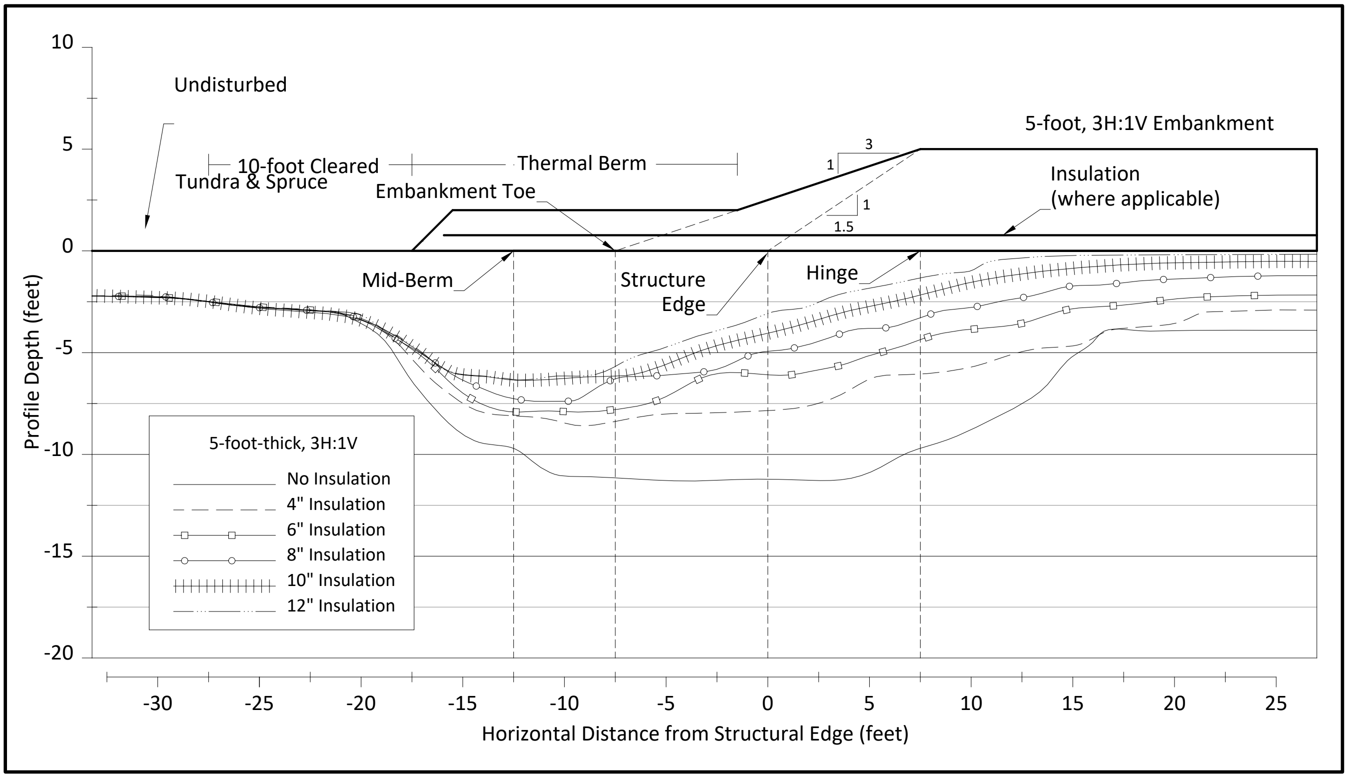


Figure B-2: Thaw Depth versus Insulation For 5-foot, 3H:1V Gravel-Surfaced Embankment
(2049, RCP6.0, mid-level emissions repeated for 19 years/18 thaw-seasons)

Table B-2: Thaw Depth versus Settlement For 5-foot, 3H:1V Gravel-Surfaced Embankment
(2049, RCP6.0, mid-level emissions repeated for 19 years/18 thaw-seasons)

Point		**Insulation Configuration**					
		NI	**4-inches**	**6-inches**	**8-inches**	**10-inches**	**12-inches**
Center	Thaw (ft.)	3.9	2.9	2.2	1.2	0.5	0.2
	Settlement (ft.)	**1.0**	**0.5**	**0.5**	**0.0**	**0.0**	**0.0**
Hinge	Thaw (ft.)	9.7	6.1	4.4	3.3	2.2	1.3
	Settlement (ft.)	**3.5**	**2.0**	**1.5**	**0.5**	**0.0**	**0.0**
Structure Edge	Thaw (ft.)	11.2	7.8	6.1	4.9	4.0	3.1
	Settlement (ft.)	**4.0**	**3.0**	**2.0**	**1.5**	**1.0**	**0.5**
Embankment Toe	Thaw (ft.)	11.1	8.4	7.8	6.3	6.2	5.7
	Settlement (ft.)	**3.5**	**3.0**	**3.0**	**2.0**	**2.0**	**2.0**

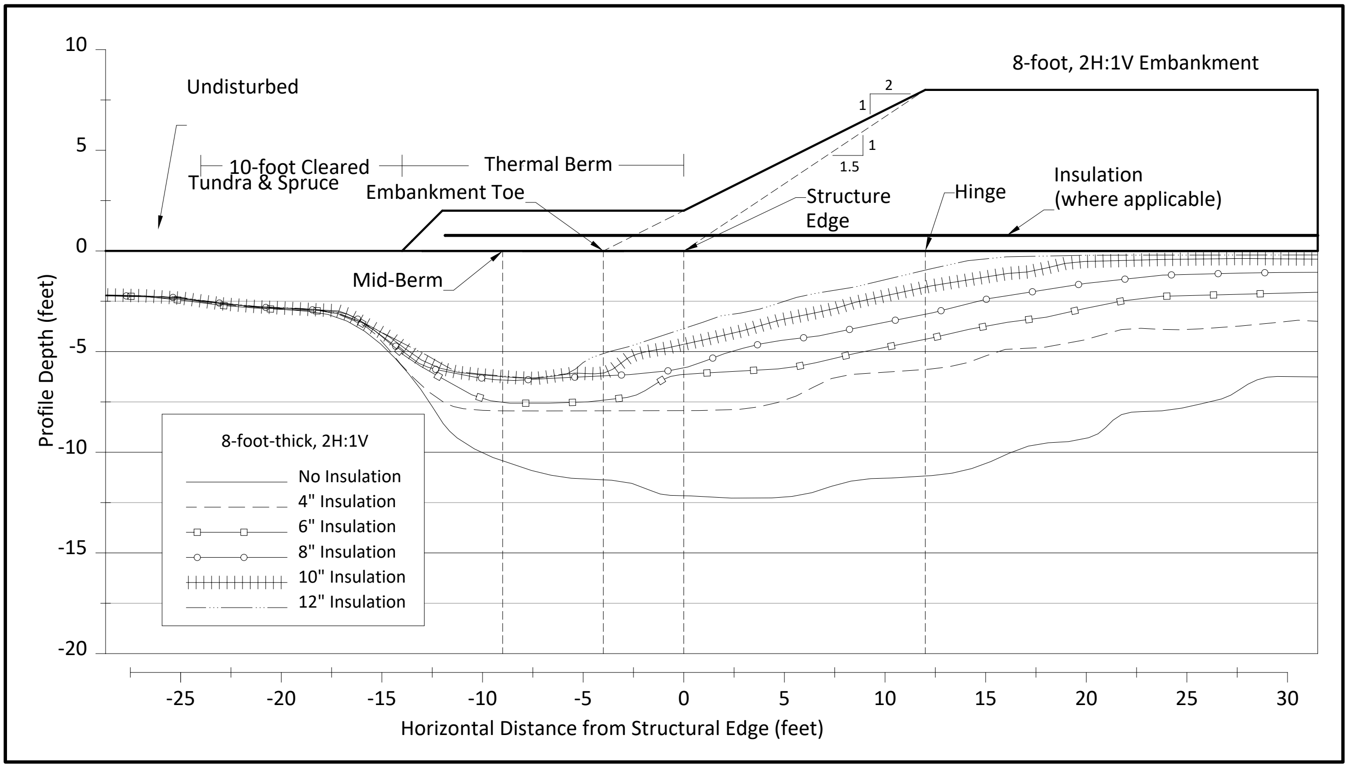


Figure B-3: Thaw Depth versus Insulation For 8-foot, 2H:1V Gravel-Surfaced Embankment
(2049, RCP6.0, mid-level emissions repeated for 19 years/18 thaw-seasons)

Table B-3: Thaw Depth versus Settlement For 8-foot, 2H:1V Gravel-Surfaced Embankment
(2049, RCP6.0, mid-level emissions repeated for 19 years/18 thaw-seasons)

Point		**Insulation Configuration**					
		NI	**4-inches**	**6-inches**	**8-inches**	**10-inches**	**12-inches**
Center	Thaw (ft.)	6.3	3.5	2.1	1.1	0.4	0.2
	Settlement (ft.)	**2.5**	**1.0**	**0.0**	**0.0**	**0.0**	**0.0**
Hinge	Thaw (ft.)	11.2	5.9	4.4	3.1	1.8	1.0
	Settlement (ft.)	**5.0**	**2.5**	**1.5**	**1.0**	**0.0**	**0.0**
Structure Edge	Thaw (ft.)	12.2	7.9	6.1	5.8	4.6	3.9
	Settlement (ft.)	**5.0**	**3.5**	**2.5**	**2.5**	**1.5**	**1.5**
Embankment Toe	Thaw (ft.)	11.4	8.0	7.4	6.2	6.1	5.1
	Settlement (ft.)	**5.0**	**3.5**	**3.5**	**2.5**	**2.5**	**2.0**

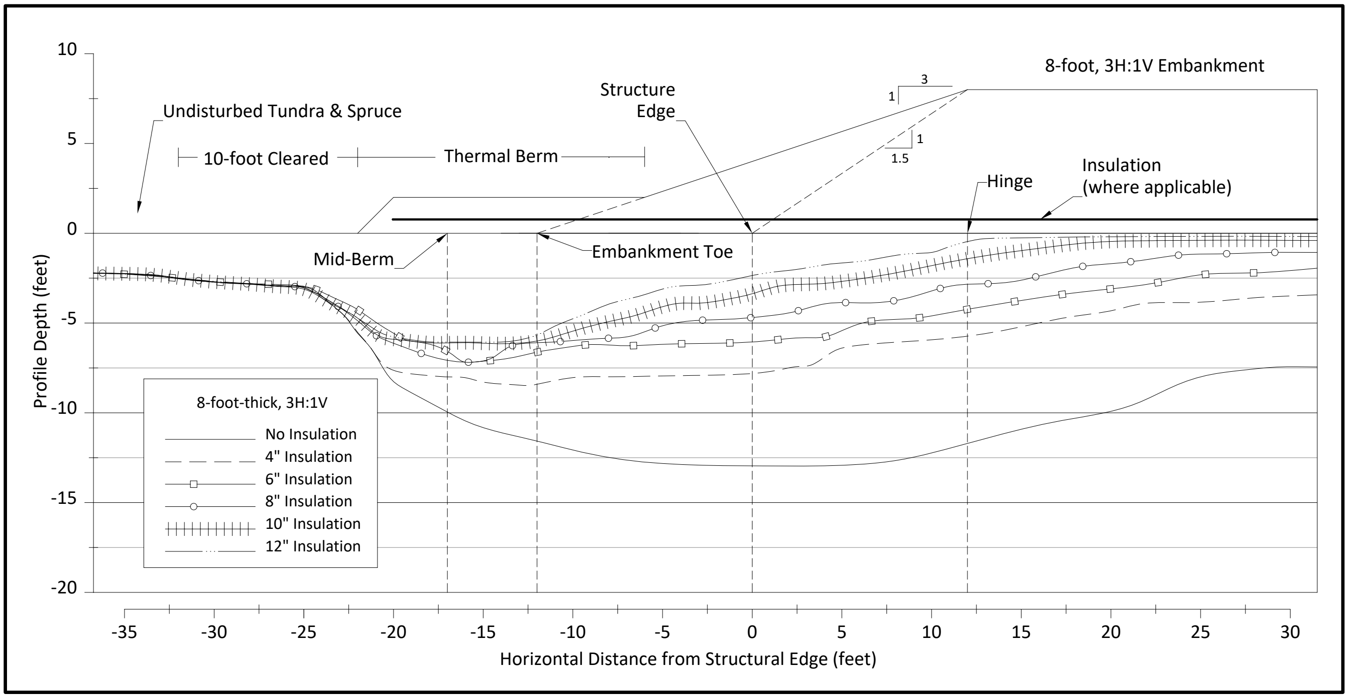


Figure B-4: Thaw Depth versus Insulation For 8-foot, 3H:1V Gravel-Surfaced Embankment
(2049, RCP6.0, mid-level emissions repeated for 19 years/18 thaw-seasons)

Table B-4: Thaw Depth versus Settlement For 8-foot, 3H:1V Gravel-Surfaced Embankment
(2049, RCP6.0, mid-level emissions repeated for 19 years/18 thaw-seasons)

Point		**Thaw (feet) For Each Insulation Configuration**					
		NI	**4-inches**	**6-inches**	**8-inches**	**10-inches**	**12-inches**
Center	Thaw (ft.)	7.4	3.4	1.9	1.1	0.4	0.2
	Settlement (ft.)	**3.5**	**1.0**	**0.0**	**0.0**	**0.0**	**0.0**
Hinge	Thaw (ft.)	11.7	5.7	4.2	2.8	1.4	0.5
	Settlement (ft.)	**5.5**	**2.5**	**1.5**	**0.5**	**0.0**	**0.0**
Structure Edge	Thaw (ft.)	13.0	7.8	6.1	4.7	3.4	2.3
	Settlement (ft.)	**6.0**	**3.5**	**2.5**	**2.0**	**1.0**	**0.5**
Embankment Toe	Thaw (ft.)	11.6	8.4	6.6	6.1	6.0	5.7
	Settlement (ft.)	**5.0**	**4.0**	**3.0**	**2.5**	**2.5**	**2.5**

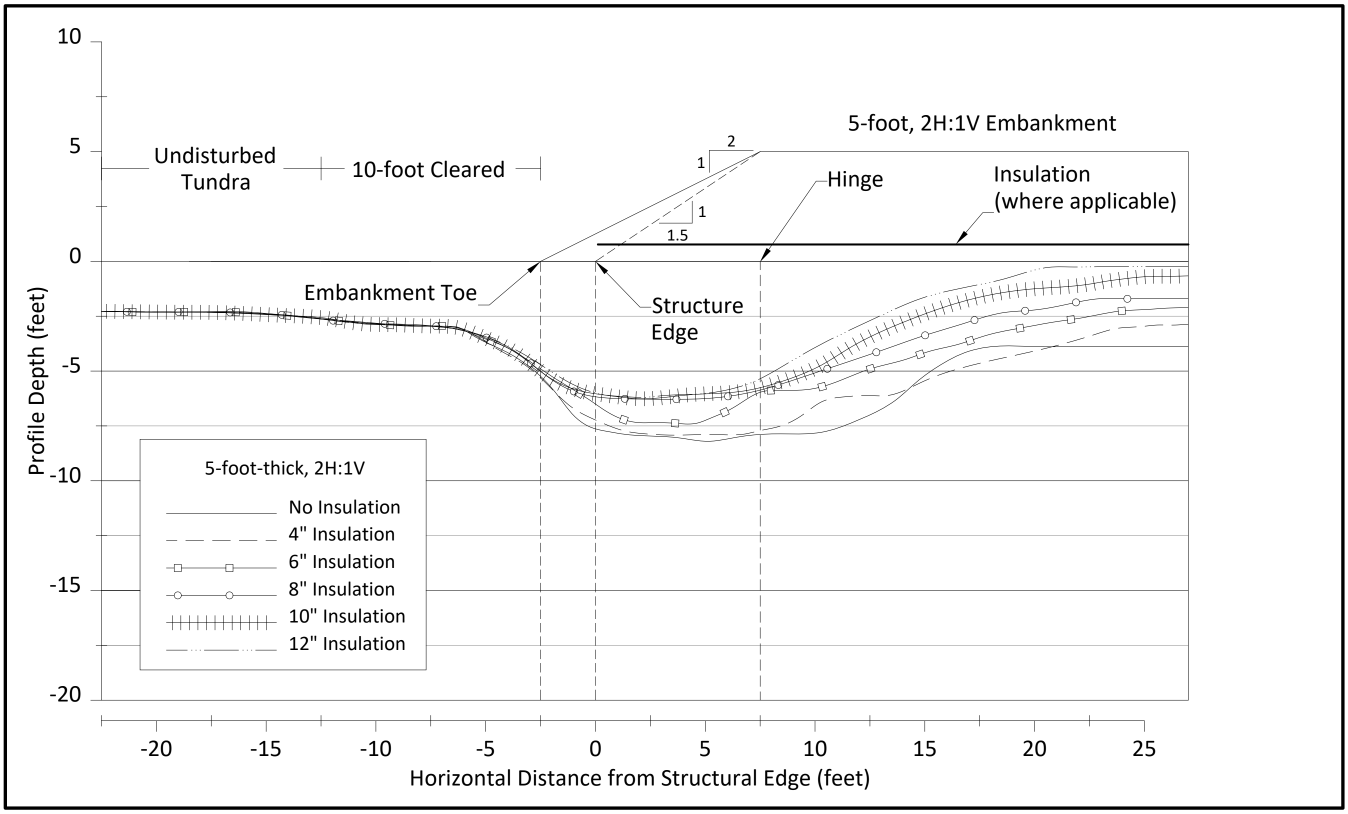


Figure B-5: Thaw Depth versus Insulation For 5-foot, 2H:1V Gravel-Surfaced Embankment
(2049, RCP6.0, mid-level emissions repeated for 19 years/18 thaw-seasons)

Table B-5: Thaw Depth versus Settlement For 5-foot, 2H:1V Gravel-Surfaced Embankment
(2049, RCP6.0, mid-level emissions repeated for 19 years/18 thaw-seasons)

Point		**Thaw (feet) For Each Insulation Configuration**					
		NI	**4-inches**	**6-inches**	**8-inches**	**10-inches**	**12-inches**
Center	Thaw (ft.)	3.9	2.9	2.1	1.7	0.7	0.2
	Settlement (ft.)	**1.0**	**0.5**	**0.0**	**0.0**	**0.0**	**0.0**
Hinge	Thaw (ft.)	7.9	7.7	6.0	5.9	5.8	5.3
	Settlement (ft.)	**3.0**	**3.0**	**2.0**	**2.0**	**2.0**	**1.5**
Structure Edge	Thaw (ft.)	7.6	7.2	6.5	6.2	6.0	6.0
	Settlement (ft.)	**2.5**	**2.5**	**2.0**	**2.0**	**2.0**	**2.0**
Embankment Toe	Thaw (ft.)	5.2	5.3	4.9	5.0	5.0	4.7
	Settlement (ft.)	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**

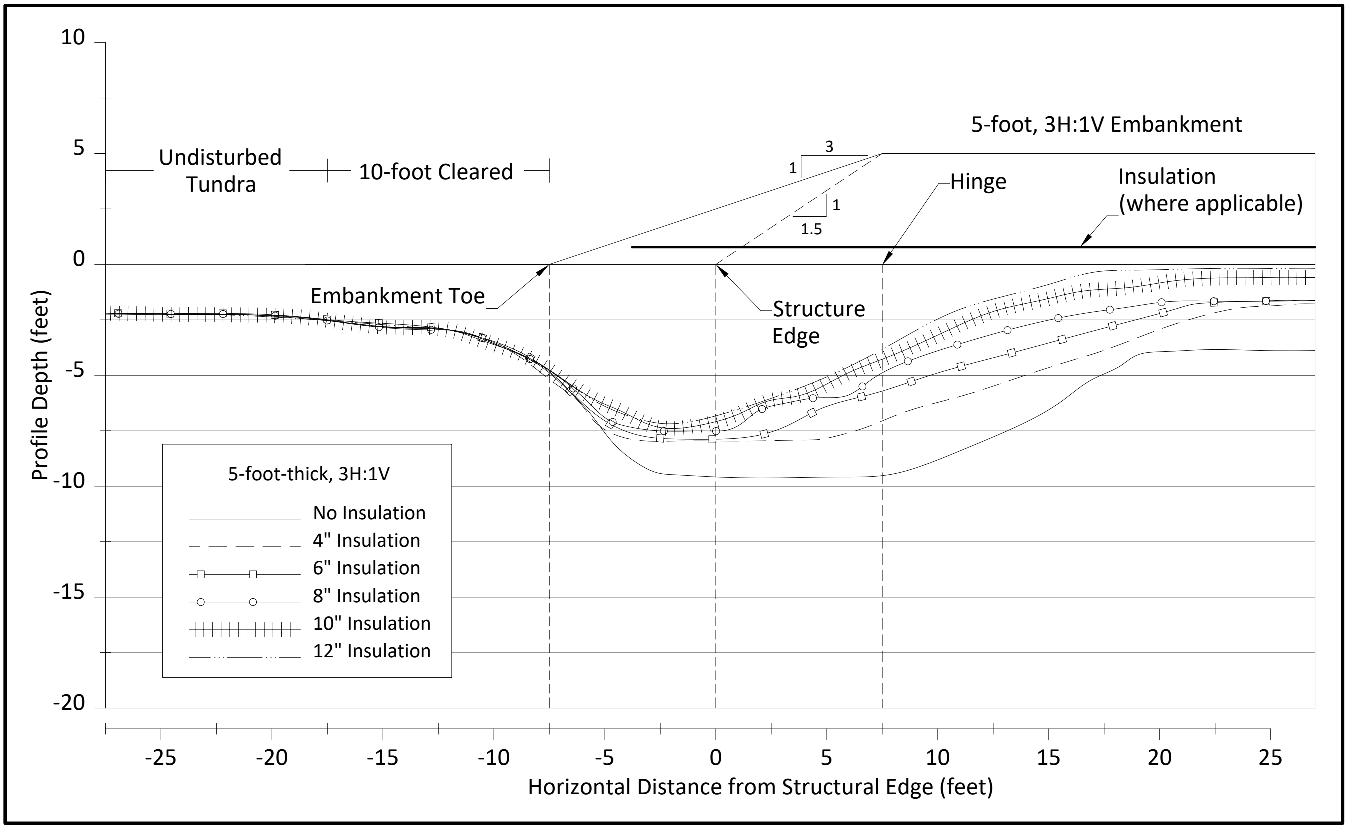


Figure B-6: Thaw Depth versus Insulation For 5-foot, 3H:1V Gravel-Surfaced Embankment *(2049, RCP6.0, mid-level emissions repeated for 19 years/18 thaw-seasons)*

Table B-6: Thaw Depth versus Settlement For 5-foot, 3H:1V Gravel-Surfaced Embankment *(2049, RCP6.0, mid-level emissions repeated for 19 years/18 thaw-seasons)*

Point		**Thaw (feet) For Each Insulation Configuration**					
		NI	**4-inches**	**6-inches**	**8-inches**	**10-inches**	**12-inches**
Center	Thaw (ft.)	3.9	1.8	1.6	1.6	0.6	0.2
	Settlement (ft.)	**1.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
Hinge	Thaw (ft.)	9.5	7.1	5.7	4.9	4.3	3.8
	Settlement (ft.)	**3.5**	**2.5**	**2.0**	**1.5**	**1.0**	**1.0**
Structure Edge	Thaw (ft.)	9.6	8.0	7.9	7.5	7.1	6.8
	Settlement (ft.)	**3.5**	**3.0**	**3.0**	**2.5**	**2.5**	**2.5**
Embankment Toe	Thaw (ft.)	4.9	5.2	4.8	4.8	4.8	4.8
	Settlement (ft.)	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**

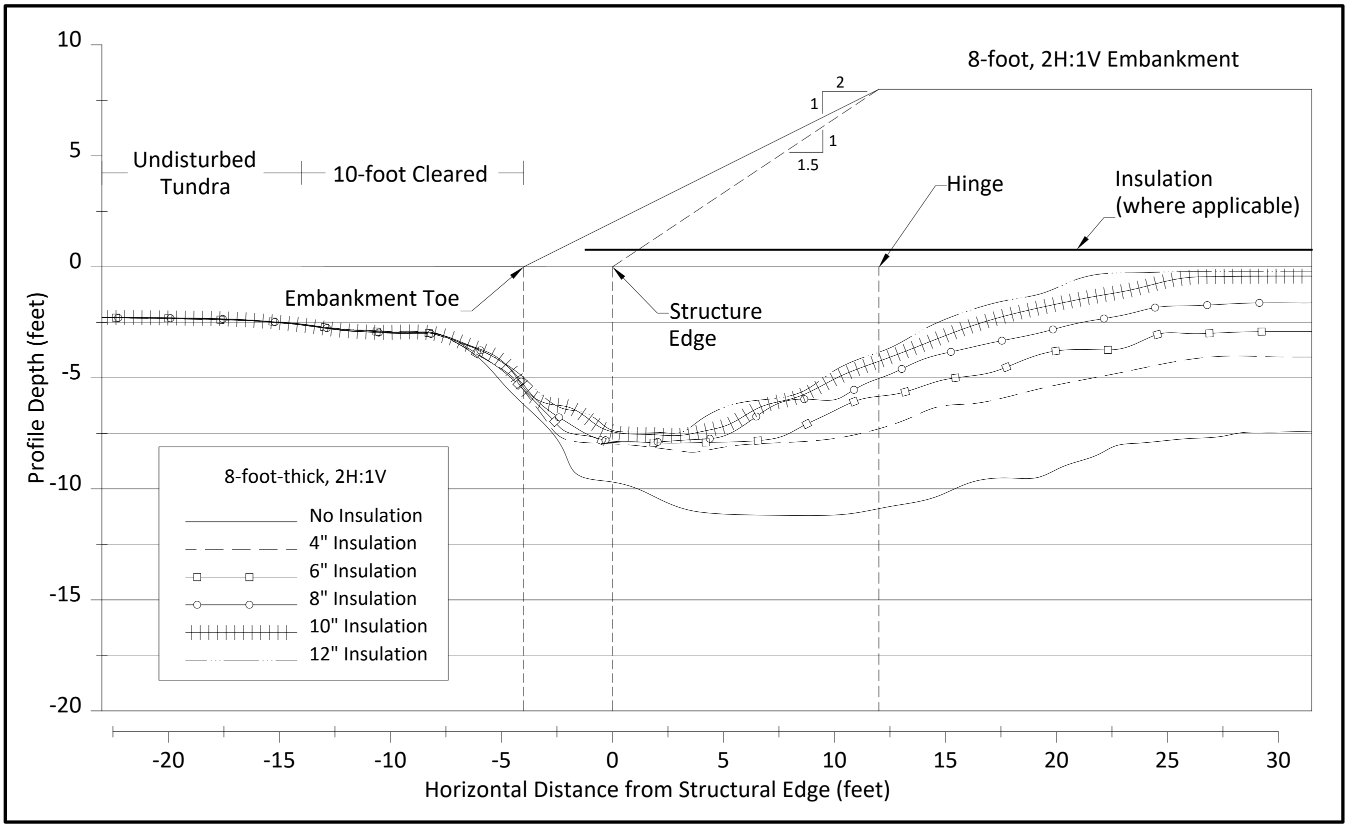


Figure B-7: Thaw Depth versus Insulation For 8-foot, 2H:1V Gravel-Surfaced Embankment
(2049, RCP6.0, mid-level emissions repeated for 19 years/18 thaw-seasons)

Table B-7: Thaw Depth versus Settlement For 8-foot, 2H:1V Gravel-Surfaced Embankment
(2049, RCP6.0, mid-level emissions repeated for 19 years/18 thaw-seasons)

Point		**Thaw (feet) For Each Insulation Configuration**					
		NI	**4-inches**	**6-inches**	**8-inches**	**10-inches**	**12-inches**
Center	Thaw (ft.)	7.4	4.1	2.9	1.6	0.4	0.2
	Settlement (ft.)	**3.5**	**1.5**	**1.0**	**0.0**	**0.0**	**0.0**
Hinge	Thaw (ft.)	10.9	7.3	5.8	5.0	4.3	3.8
	Settlement (ft.)	**5.0**	**3.5**	**2.5**	**2.0**	**1.5**	**1.0**
Structure Edge	Thaw (ft.)	9.7	8.0	7.9	7.9	7.4	7.4
	Settlement (ft.)	**4.5**	**3.5**	**3.5**	**3.5**	**3.5**	**3.5**
Embankment Toe	Thaw (ft.)	6.2	5.6	5.5	5.3	5.4	5.0
	Settlement (ft.)	**2.0**	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**

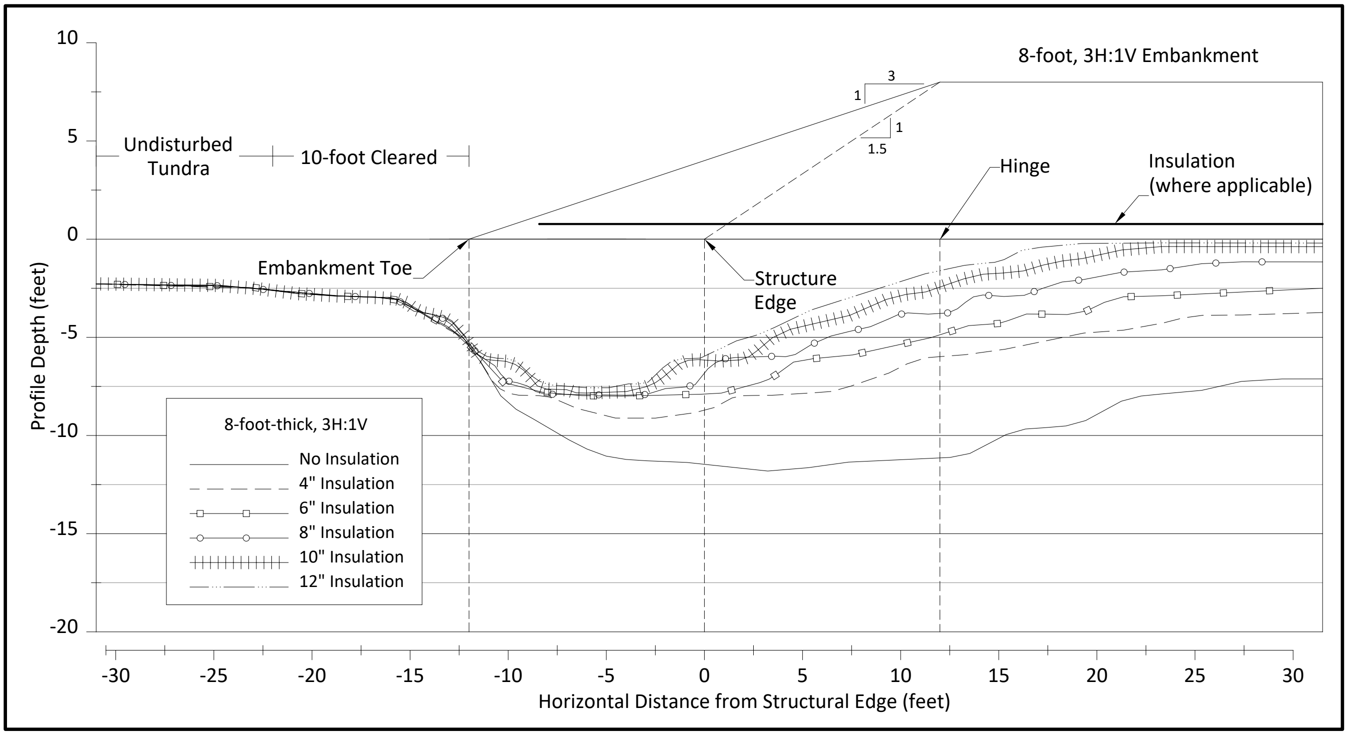


Figure B-8: Thaw Depth versus Insulation For 8-foot, 3H:1V Gravel-Surfaced Embankment
(2049, RCP6.0, mid-level emissions repeated for 19 years/18 thaw-seasons)

Table B-8: Thaw Depth versus Settlement For 8-foot, 3H:1V Gravel-Surfaced Embankment
(2049, RCP6.0, mid-level emissions repeated for 19 years/18 thaw-seasons)

Point		**Thaw (feet) For Each Insulation Configuration**					
		NI	**4-inches**	**6-inches**	**8-inches**	**10-inches**	**12-inches**
Center	Thaw (ft.)	7.1	3.7	2.5	1.2	0.4	0.2
	Settlement (ft.)	**3.0**	**1.0**	**0.5**	**0.0**	**0.0**	**0.0**
Hinge	Thaw (ft.)	11.1	6.0	4.9	3.8	2.5	1.6
	Settlement (ft.)	**5.0**	**2.5**	**2.0**	**1.0**	**0.5**	**0.0**
Structure Edge	Thaw (ft.)	11.5	8.7	7.9	6.8	6.2	6.0
	Settlement (ft.)	**5.0**	**4.0**	**3.5**	**3.0**	**2.5**	**2.5**
Embankment Toe	Thaw (ft.)	5.5	5.4	5.3	5.4	5.3	5.2
	Settlement (ft.)	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**

Appendix C

Alaska DOT&PF Northern Region Thermal Modeling and Thaw-Settlement Estimation Pratice and Procedures

Thermal modeling with TEMP\W requires the development of the foundation soil profile, measurement or estimation of soil physical and thermal properties, upper and lower boundary conditions, assumptions regarding future climate conditions and development of design alternatives for road or airport embankment configurations. When it is anticipated that thermal modeling will be required for a highway project, measurement of air and ground temperatures, excavation of test pits to characterize the organic mat and near-surface ground conditions, and thaw-depth (active layer) probing should be added to the project geotechnical investigation.

The development of a reasonably accurate thermal model is critically dependent upon:

- Measurement or estimation of site-specific air temperatures
- Development of a foundation soil profile and soil physical and thermal properties, and
- Measurement of ground temperatures at depth and active layer thickness to allow for model calibration.

Drilling, Sampling, Laboratory Testing and Ground Temperature Measurements:

Highway and airport projects typically require a geotechnical investigation that includes drilling, sampling and laboratory testing. Existing embankments and foundation soils layers should be characterized and logged. Representative samples for both the existing embankment and foundation soil layers should be tested in the laboratory for gravimetric moisture, gradation and organic content. A PVC conduit should typically be installed in a borehole and the borehole backfilled with cuttings to allow for future recovery of the digital temperature cable used for ground temperature measurement. The ground temperatures will be later used in thermal model calibration. A single-point digital temperature cable should be installed in a radiation shield for air temperature measurement. Site air and ground temperatures should be recorded for as long as the project schedule will allow.

Site Test Pitting, Near-Surface Foundation Soil Characterization, and Active Layer Thickness Measurement:

Where highway project include new alignments, test pits should be excavated though the organic mat and into the active layer. Test pitting should occur, if possible, in the fall when maximum thaw depths are anticipated. Individual layers should be characterized and soil layers below the organic mat should be sampled for laboratory testing and thermal conductivity measurements. Moisture conditions should be assessed. Thaw depth (assumed active layer thickness) should be determined by probing with a steel rod. Results of the test pitting and laboratory testing will be used to refine the upper foundation soil layers in the thermal models. Active layer thickness will be used in the calibration of the thermal models.

Development of Typical Foundation Soil Profile:

The foundation soil profile should be developed based upon the drill logs and laboratory test results for the project and also the test pits excavated to evaluate the organic mat and near-surface soil layers. Figure C-1 illustrates the soil profiles based on geotechnical drilling along the Frozen Debris Lobe Realignment on the Dalton Highway MP 209-222 Project.

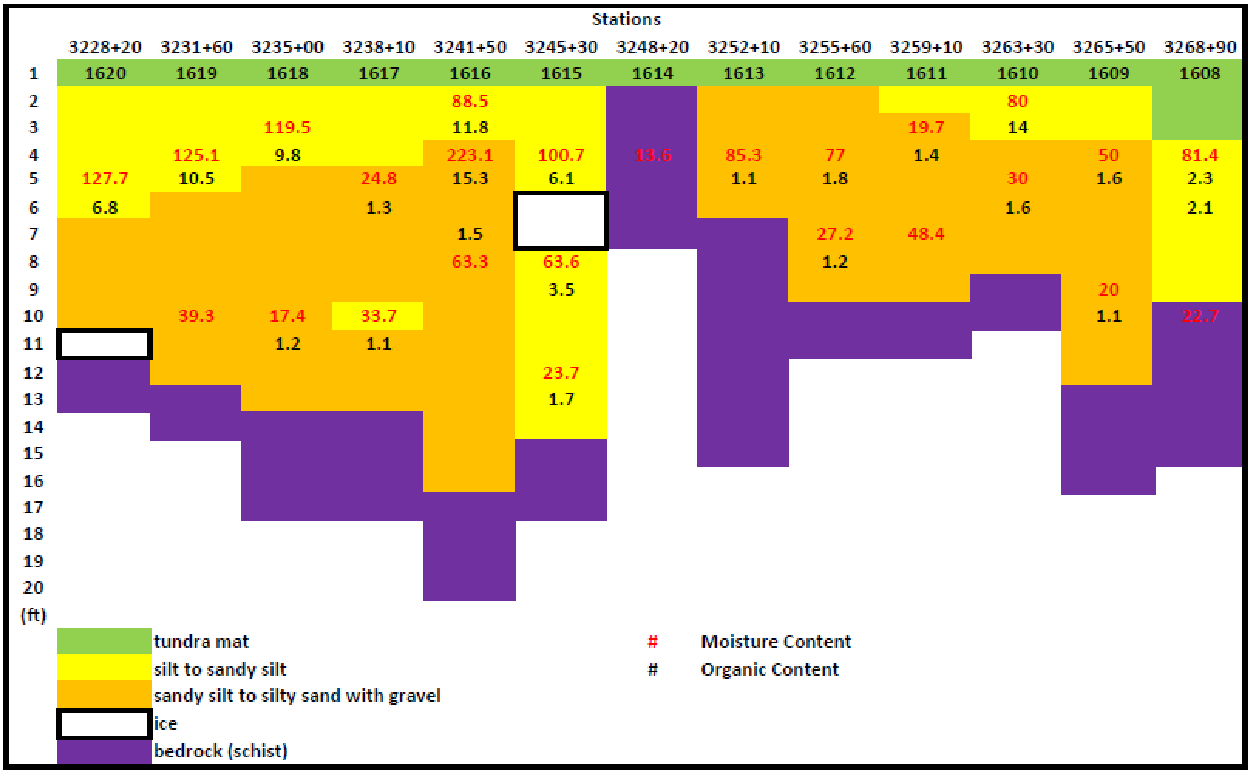


Figure C-1. Foundation soil profile along Dalton Highway Frozen Debris Lobe Realignment.

A test hole should be selected, or a typical foundation soil profile should be created, that represents typical foundation soil properties for “ice-rich” foundation soils. The organic mat and near-surface soils should be divided into separate layers. The foundation soil profile will then be used to model the existing ground conditions without the road or airport embankment. The model will be calibrated by adjusting n-factors and material properties until the modeled ground temperatures and active layer thickness reasonably compare to measured ground temperatures and active layer thickness.

The reliability of the embankment design recommendations hinges on the development of an appropriate foundation soil profile. The geologic setting of the highway or airport project and the results of the geotechnical investigation will determine whether a single foundation soil profile is a reasonable assumption for the entire project or whether the thermal modeling efforts need to consider different foundation soil profiles.

Upper Boundary Conditions - Air and Near-Surface Ground Temperature Data and n-Factors:

Long-term records for air temperatures, near-surface ground temperatures, and ground temperatures at depth are not available for most projects. Shorter-term records for air and ground temperatures should be collected at the site as part of the geotechnical investigation. The site air temperature record should be compared to nearby long-term weather station record to evaluate which long-term weather station most closely matches the site conditions and how this long-term station record should be adjusted to create a "long-term site specific" temperature record for development of the upper boundary condition in the thermal model.

Most projects do not have the requisite year-long measurement of air and near-surface ground temperatures needed to calculate n-factors. Appropriate n-factors must be assumed for the project embankment, undisturbed surrounding ground cover and also the cleared zone. These n-factors will be used to "convert" air temperatures to ground surface temperatures, and will be "adjusted" to calibrate the thermal model.

The upper boundary condition for the thermal model should be based on site historic and predicted future air temperatures and appropriate n-factors derived from literature or past thermal modeling experience for the embankment materials, undisturbed forest or tundra and for the case of tree-clearing but no grubbing of the vegetative mat in the highway or airport clearing zone. The initially selected n-factors will then be modified as necessary to complete the calibration of the thermal model. Final n-factors required for model calibration should then be compared to those found in literature and those used in past modeling efforts to ensure they are reasonable. The calculated and then adjusted n-factors for the Dalton Highway MP 0-9 Realignment Project are shown in Table 1.

The n-factors for gravel road surface and side slopes and the n-factors for ACE embankments should be based on accepted values found in relevant literature and past thermal model calibration efforts.

Table C-1 – Dalton Highway MP 0-9 Project n-Factors

Vegetation	Calculated n_f	Calculated n_t	Adjusted n_f	Adjusted n_t
Spruce Forest (sparse trees) and Tundra - Undisturbed	0.48	0.71	0.46	0.71
Spruce Forest (sparse trees) and Tundra – Hand-Clearing of Trees	0.50	0.96	0.47	0.92

It is important to note that even the hand-clearing of trees with no disturbance to the tundra mat, caused the calculated thawed or summer n-factor to increase from 0.71 to 0.96. The take away from this is that clearing should be kept to the minimum required for public safety consideration wherever ice-rich foundations soils require the construction of ACE Embankments or Insulated Embankments. The clearing at these locations should be accomplished in a manner that minimizes disturbance to the tundra mat; this may require either hand-clearing or seasonal restrictions on mechanized clearing.

Lower Boundary Conditions - Geothermal Flux:

Thermal model lower boundary conditions are typically either a fixed temperature at depth or an assumed geothermal flux. If a sufficiently long-term ground temperature record is available for the specific project; or from nearby permafrost monitoring stations; the ground temperature profile vs. time can be examined to determine of the measured temperature at the depth of no-annual temperature change. The fixed temperature at depth can be used for short-term thermal models and to calibrate the thermal model.

Site-specific ground temperatures should be used when available to determine the measured temperature at the depth of no-annual temperature change to allow for calibration of the model soil layer thermal properties and then the site specific heat flux. If the site-specific ground temperature record does not allow for determination of the measured temperature at the depth of no-annual temperature change, the Permafrost Laboratory web page at the UAF Geophysical Institute should be reviewed to determine if there is ground temperature data within a reasonable distance from the project site that can be used to estimate the temperature at the depth of no-annual temperature change or calculate the geothermal heat flux for thermal model calibration. http://permafrost.gi.alaska.edu/sites_map

The geothermal heat flux for the Dalton Highway MP 0-9 Thermal Model was determined by first fixing the ground temperature to equal the measured temperature at the depth of no-annual temperature change. The model was then calibrated using this fixed temperature at depth. Once the surface n-factors and physical and thermal properties of the upper soil layers were modified as necessary to calibrate the model, the temperature at depth was un-fixed and a geothermal gradient of 0.60 Btu/day*ft^2 was applied as a lower boundary condition. The heat flux was then adjusted until the modeled temperature at depth matched the measured and originally fixed temperature at depth. The Lower Boundary Condition was estimated to be 0.35 Btu/day*ft^2 for the Dalton Highway MP 0-9 Project.

If a sufficiently long-term project ground temperature record is not available to allow determination of the measured temperature at the depth of no-annual temperature change and there is no ground temperature data available reasonably close to the project, it will be necessary to assume a geothermal flux for the project location. An updated heat flow map for Alaska has been developed by SMU Geothermal Laboratory; https://pangea.stanford.edu/ERE/db/WGC/papers/WGC/2015/11080.pdf

The geothermal flux can be estimated from the 2015 Heat Flow Map of Alaska as discussed in the above link; the updated heat-flow map is shown in Figure C-2.

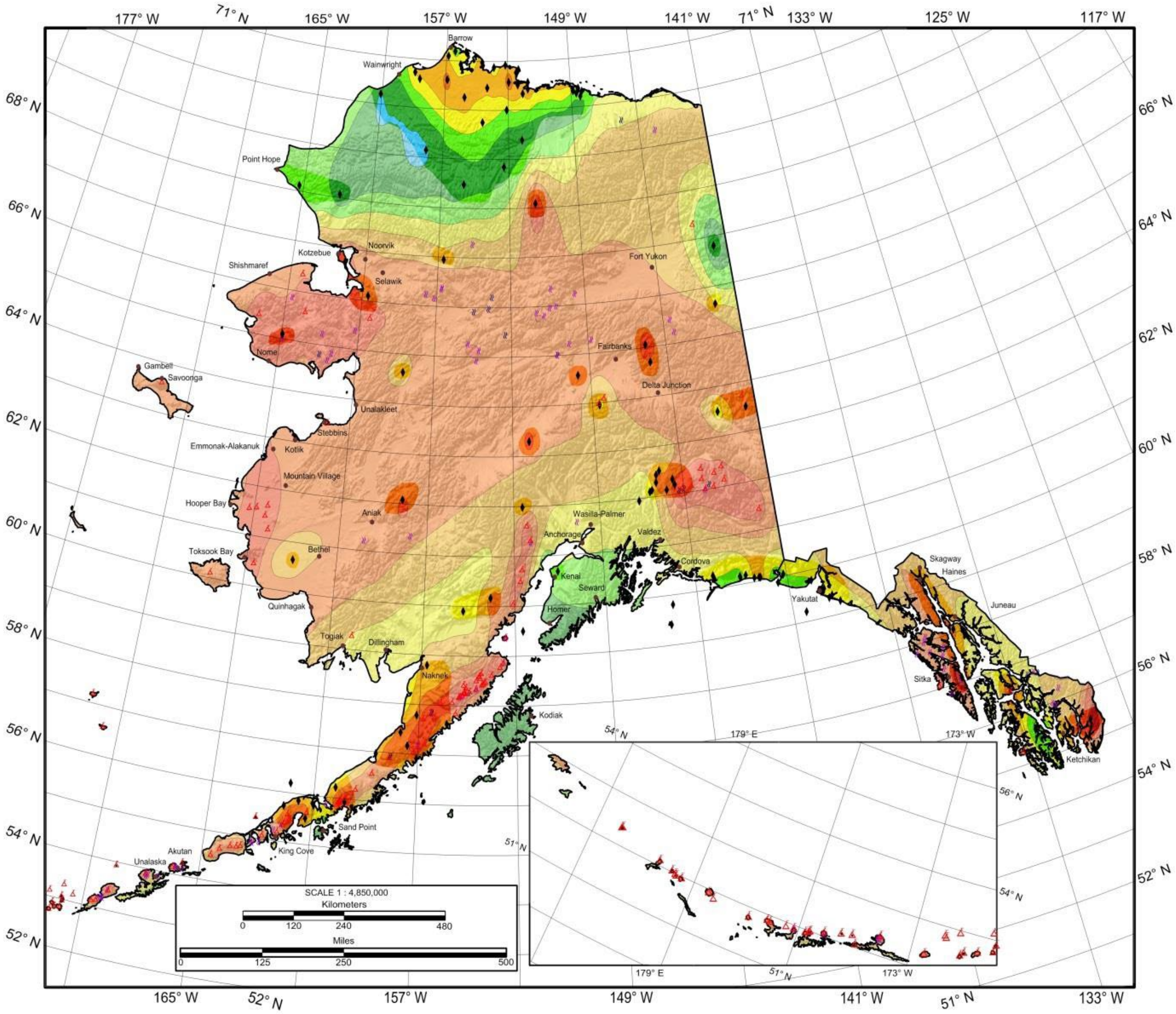


Figure C-2. Updated Heat flow Map of Alaska (2015).

Soil Profile after Embankment Construction:

The upper layers of the Foundation Soil Profile need to be modified based on the assumption that any live moss, dead moss, silty-peat and thawed organic-rich silt would be compressed under the loading of the embankment and their thermal properties and moisture content would change. In the thermal modeling of the Dalton Highway MP 0-9 Realignment Project, it was assumed that the 0.8-foot thick layer of Thawed Organic Silt in the active layer would be compressed to become a 0.5-foot thick layer of Wet-Compressed Thawed Organic Silt. It was further assumed the 0.25-foot thick layer of Live Moss, the 0.25-foot thick layer of Dead Moss and the 0.5-foot thick layer of Silty-Peat would be compressed into a 0.25-foot thick layer of Wet-Compressed Organic Mat (and Silty Peat). The space previously occupied by the Silty-Peat and the Dead Moss was replaced with Wet Selected Material (Borrow) and the space previously occupied by the Live Moss was replaced with Selected Material (Borrow – Dry). Thermal properties and volumetric water content were estimated for the new "compressed" materials. A similar method should be done for future project based on the near-surface soil profile developed from test pitting and drilling.

Soil Thermal Properties and TEMP/W Model Calibration:

The soil thermal properties used during thermal model calibration need to be developed through a combination of using laboratory test results, referring to literature and other resources, making reasonable assumptions, and employing an iterative approach between analyzing model results and adjusting estimated soil thermal properties. Whenever possible, we utilize the methods found in A Generalized Thermal Conductivity Model for Soils and Construction Materials - Côté & Konrad (2005). In the thermal modeling of the Dalton Highway MP 0-9 Realignment Project, we calibrated the model and soil thermal properties by comparing modeled and measured freezing and thawing indices with depth, as well as the modeled and measured time-dependent temperature profile at the base of each soil layer. Our n-factors and our soil thermal properties were adjusted to approximate a best fit between these modeled and measured values. A similar approach should be followed if project specific ground and air temperatures are available.

TEMP/W Model Development with Projected Future Air Temperatures

On the Dalton Highway MP 0-9 Realignment Project, once we calibrated the model based on historic site specific air temperatures, we applied future temperatures to models that incorporated various embankment configurations. Our future temperature profiles are developed by applying a projected temperature increase to a 365-day temperature cycle. In the thermal modeling of the Dalton Highway MP 0-9 Realignment Project, the 365-day cycle was developed from averaging 8-years of daily temperatures recorded at the nearby Livengood Airport Weather Station and subtracting 1-°F to adjust the Livengood Airport Weather Station Temperatures to Project Temperatures. This 365-day temperature profile was then projected forward with a temperature increase that approximated that predicted by the SNAP RCP 6.0 Mid-Level Emissions Model. We ran thermal models for various road embankment configurations for roughly 19-years or 18-thaw seasons using a repeat of the projected future air temperature for 2050.

SNAP, or Scenarios Network for Alaska + Artic Planning, provides future air temperature projections for different levels of world-wide CO2 emissions. Future projected air temperatures were derived from the annual increased suggested by the SNAP Community Chart for Livengood, Alaska under RCP 6.0 level emissions as shown in Figure C-3 and found at the following link:

https://www.snap.uaf.edu/sites/all/modules/snap_community_charts/charts.php

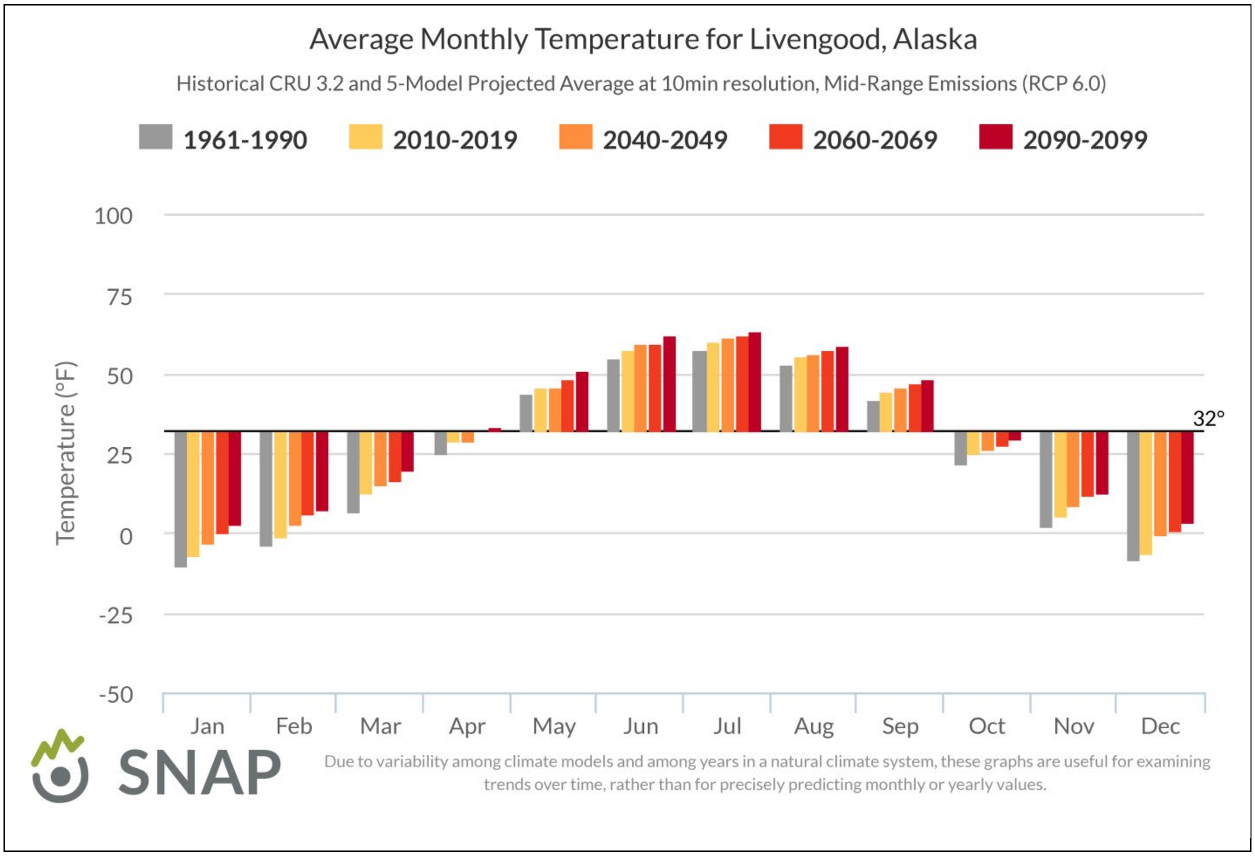


Figure C-3. Projected average monthly temperatures for Livengood, Alaska, Mid-Range Emissions.

(Note – Since completion of this research program, Northern Region of Alaska DOT&PF has determined that future air temperatures should be projected based upon SNAP (Scenarios Network for Alaska + Arctic Planning) RCP 8.5 high-level emissions model.)

Road or Airport Embankment Geometry:

The thermal model should be developed for the embankment typical section that will be constructed for the project. In the thermal modeling of the Dalton Highway MP 0-9 Realignment Project, a 39-foot wide top was selected to be consistent with new construction and other projects in this area. Generally, embankment foreslopes in fill sections were assumed to be 3H:1V for embankment heights up to 8 feet, and 2H:1V for embankment heights 8 feet and greater.

Thaw-Settlement Estimation:

The basic purpose of thermal model development is to be able to predict changes to the existing active layer depth under and adjacent to the proposed road embankment. In the thermal modeling of the Dalton Highway MP 0-9 Realignment Project, the Soil Profile after Road Construction was used to model the depth of thaw under the “No-Settlement Assumption”; under this simplifying assumption, the Soil Profile after Road Construction was not modified each year to account for thaw-settlement. It is believed that this assumption will under-predict thaw depths for the various embankment configurations.

Thermal models were run for the following road embankment configurations:
1) 5-foot embankment 3H:1V side slopes
2) 5-foot embankment 3H:1V side slopes and thermal berms
3) 8-foot embankment 2H:1V side slopes
4) 8-foot embankment 2H:1V side slopes and thermal berms
5) 8-foot embankment 3H:1V side slopes
6) 8-foot embankment 3H:1V side slopes and thermal berms

All embankment configurations were run with no insulation, 4, 6, 8, 10 and 12 inches of insulation board. Only the no-insulation, 4, 6, 8-inch configurations were analyzed for thaw-settlement.

Thaw-Settlement Assessment

The settlement that would result under each analyzed embankment configuration was estimated by applying the modeled thaw-depth for each embankment to an algorithm that estimated settlement in accordance to soil type and character. This was done for each test hole drilled along the length of the alignment. An alternative method of estimation of thaw settlement based on thaw consolidation testing conducted by the Alaska University Transportation Center for the Dalton Nine Mile Hill Project was also applied to each test hole along the alignment. There was very good correlation between the results generated by the two methods.

The measure of performance for a given embankment along the length of the alignment was based upon three basic criteria:

- Total settlement at the embankment hinge;
- Differential settlement between the embankment center and hinge point; and,
- Differential settlement between the embankment hinge point and structural edge.

Total settlement at hinge (as an indicator of likelihood of longitudinal differential settlement) > 2.0 feet = embankment configuration “fails”.

Transverse differential settlement between centerline and embankment hinge point > 1.5 feet = embankment configuration “fails”.

Transverse differential settlement between embankment hinge point and structural toe of 8-foot embankment > 2.0 feet = embankment configuration “fails”.

Transverse differential settlement between embankment hinge point and structural toe of 5-foot embankment > 1.0 feet = embankment configuration “fails”

Our final embankment recommendations were developed while analyzing these embankment performance measures and comparing them to our best judgment and understanding of preferred embankment geometry for any given location within the alignment.

A similar process would need to be developed for each project that incorporates project specific design needs.

Appendix D

Budget

Geotechnical Asset Management through Thermal Modeling and Post-Construction Thermal Monitoring of Highway embankments for the Dalton Highway MP 0-9 Reconstruction Project

Description	Quantity	Cost / Unit	Original Estimated Cost	Actual Total Cost
NRMS costs for DTC installation and maintenance.	1	$20,500	$20,500	$19,307
DTCs for pre-embankment borehole	2	$4,254	$8,508	$8,508
Snow Depth Sensor	2	$430	$860	$860
Ground Surface DTC (1-ft)	2	$861	$1,722	$1,722
D405 Satellite Data Logger	2	$3,125	$6,250	$6,250
Telemetry & data delivery service $700 / logger / year - 2.5 years	3	$1,750	$5,250	$6,321
Stainless steel single point DTC for air temperatures	5	$195	$975	$975
Radiation shield for air temperatures	3	$170	$510	$510
DTC Extension	2	$460	$920	$442
Miscellaneous Supplies	1	$2,000	$2,000	$737
Shipping	1	$200	$200	$355
Personnel Services for site visits, thermal modeling, analysis, and report compilation	1	$50,000	$50,000	$57,449*
Personnel Services for Research and T2	1	$5,000	$5,000	$200
GeoStudio AIR/W and SEEP/W for modeling of ACE Embankments	1	$6,500	$6,500	$0
Contingency (10%)	1	10%	$11,000	$0
		Sub-Total	$120,000	$103,636
ICAP (4.79% on non-labor costs)		4.79%	$5,500	$4,928
		Total:	**$125,500**	**$108,564**

- Personnel Services costs through 12/19/18.