Some Considerations in Cold Climate Geotechnical Thermal Design

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- ## Climate Data

In my consulting practice I am often asked to conduct geotechnical thermal analyses of foundation systems. A recent facility under design in Teller, Alaska required accessing climate data to support the analysis. Teller is 71 miles north-northwest of Nome, Alaska via the Bob Blodgett Nome-Teller Memorial Highway on the Seward Peninsula. Global Summary of Day (GSOD) climate data available for the Teller Airport for years 2009 through 2019 were downloaded from the NOAA's National Climatic Data Center website. These daily data were averaged over the 11-year period**. It is noted that at rural sites in Alaska climate data may not be available at all and if available may have many gaps where data are missing**. In the case of Teller Airport, data are recorded via AWOS (Automated Weather Observation Station) and approximately 20% of the data are missing on an average annual basis for the 2009-19 window.

Clients generally want to know the impact of climate change on the design of their facilities. Of course, this is critically import when designing foundation systems sited on ice-rich non-thaw-stable permafrost soils. SNAP (Scenarios Network for Alaska + Arctic Planning) data which are available on the web are generally used as a source for future climate predictions. SNAP is part of the International Arctic Research Center at the University of Alaska Fairbanks.

The following description was copied from the SNAP website: "Representative Concentration Pathways, RCPs, describe paths to future climates based on atmospheric greenhouse gas concentrations. They represent climate futures—scenarios—extrapolated out to the year 2100, based on a range of possible future human behaviors. RCPs provide a basis for comparison and a "common language" for modelers to share their work.

The RCP values 4.5, 6.0, and 8.5 indicate projected radiative forcing values.

•RCP 4.5 — "low" scenario. Assumes that new technologies and socioeconomic strategies cause emissions to peak in 2040 and radiative forcing to stabilize after 2100.
•RCP 6.0 — "medium" scenario. Assumes that emissions peak in 2080 and radiative forcing stabilizes after 2100.
•RCP 8.5 — "high" scenario. Emissions increase through the 21st century.

Making climate projections requires use of historical data as a starting point, or baseline. It's challenging to estimate historical data across a map grid because these data are only available from a few climate stations across Alaska and western Canada. Also, stations are often clustered in low-lying communities rather than across remote locations such as mountain ranges. Ideally, estimates should be made at regular intervals, or on a grid."

Teller's RCP 8.5 data were downloaded from the SNAP website. These data are presented as predicted monthly temperatures for decadal windows starting with 2000-09 through 2090-99 and a graphical presentation of these data are shown in Figure 1.

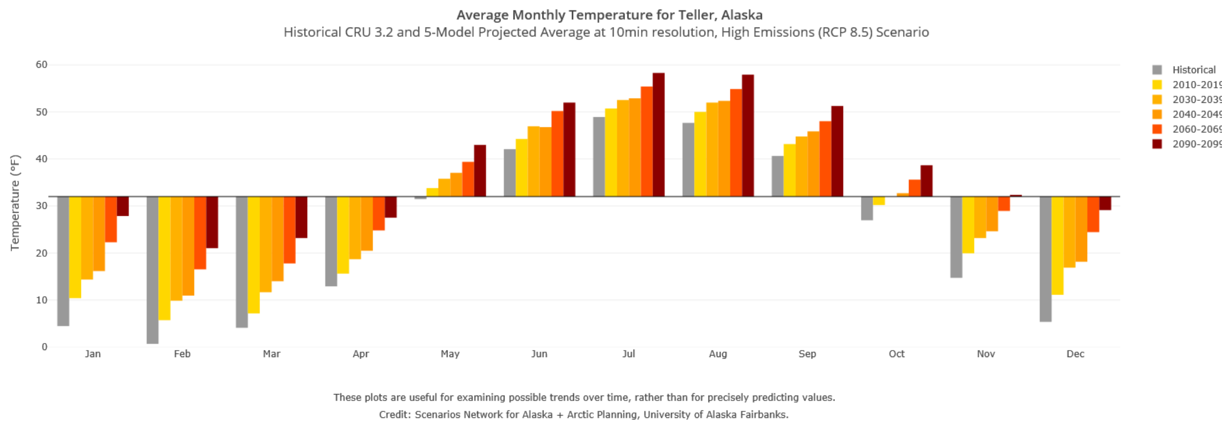

Figure 1. Teller RCP 8.5 climate projections and historical baseline.

From Teller's RCP 8.5 monthly projected temperatures, annual freezing and thawing indices were calculated for each decadal period. These indices were used to determine corresponding mean annual air temperatures and amplitudes of a sinusoidal function and are listed in Table 1. These mean annual air temperatures and amplitudes yield identical freezing and thawing indices, upon integration of the areas bounded by the sinusoidal function and the freezing isotherm, as those calculated from SNAP data.

The sinusoidal function is $T(t) = T_m - A_O * \cos(2\pi(t-\phi)/365)$, where T is air temperature, Tm is mean annual air temperature, A_O is amplitude of the cosine function, t is time in days, and ϕ is phase lag in days measured from January 1. It is commonly used in geotechnical finite element thermal modelling to specify surface temperatures by applying n-factors.

Annual freezing and thawing indices were calculated from the Teller Airport 2009-19 averaged daily data. Mean annual air temperature and amplitude of the sinusoidal function from these freezing and thawing indices were then calculated and also shown in Table 1.

Date Range	AFI	ATI	Tmean	Ao
Actual 2009-19	3,823	2,102	27.3	25.1
2010-2019	3,732	1,896	27.0	23.7
2020-2029	3,241	2,062	28.8	22.6
2030-2039	2,930	2,204	30.0	22.0
2040-2049	2,635	2,315	31.1	21.3
2050-2059	2,287	2,569	32.8	20.9
2060-2069	1,718	2,800	35.0	19.2
2070-2079	1,617	2,906	35.5	19.1
2080-2089	1,139	3,121	37.4	17.5
2090-2099	933	3,353	38.6	17.1

Table 1. Actual Teller Airport data averaged over 2009-19 and SNAP predicted decadal data.

Results presented in Table 1 clearly show a predicted warming trend. With mean annual air temperatures projected to exceed 32°F by mid-21st century, permafrost degradation is destined to occur. It is noted that the average mean annual temperature for 2009-19 at the Teller Airport slightly exceeds the RCP 8.5 mean annual decadal temperature projected by SNAP. **Designers will have to decide which RCP scenario is appropriate for their specific project.**

Figure 2 shows the sinusoidal functions calculated for the actual Teller Airport data and the SNAP RCP 8.5 projected data. Also shown is the average actual daily temperature data for the years 2009-19.

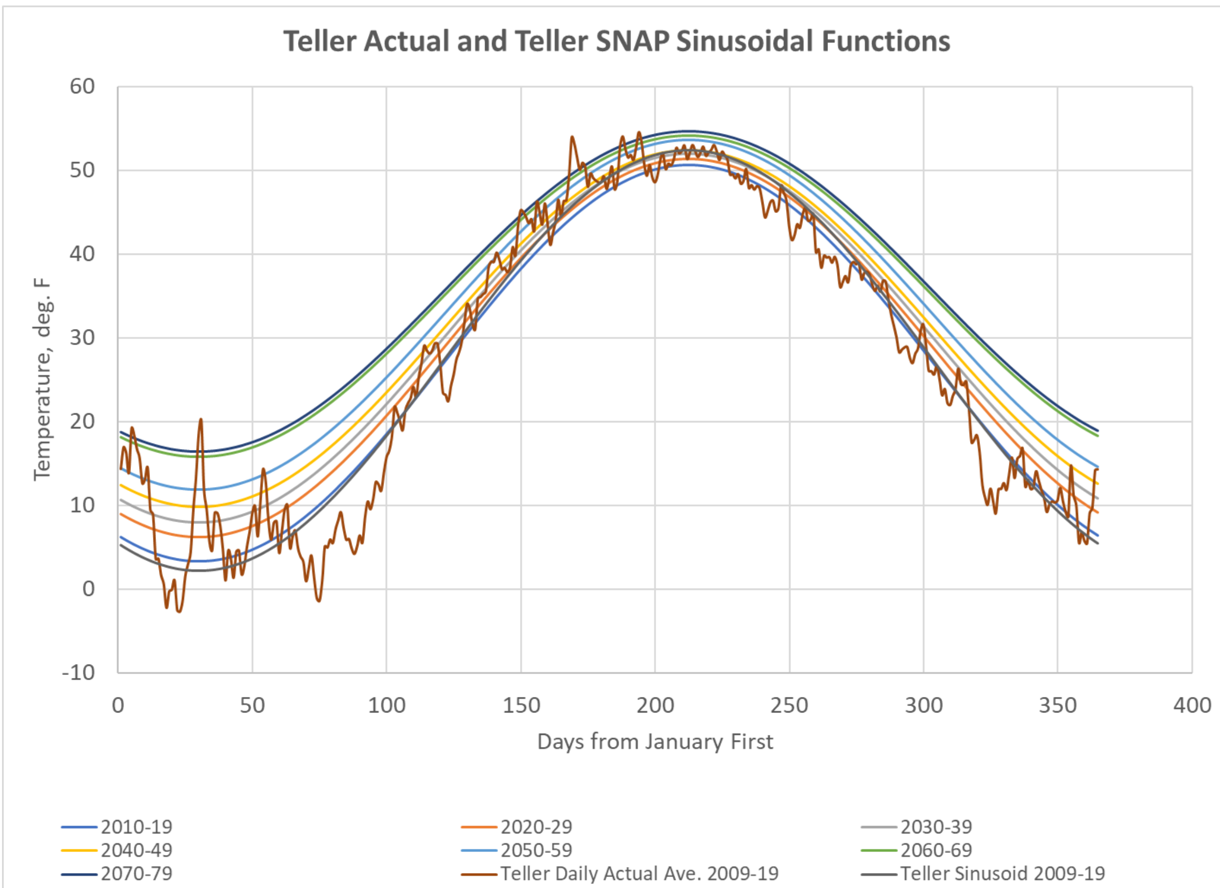

Figure 2. Teller Airport average daily data for 2009-19 and sinusoidal functions based on actual Teller and SNAP Teller freezing and thawing indices.

- **Soil Thermal Conductivity**

Thermal conductivity of frozen and unfrozen soils underlying on-grade facilities such as buildings designed for cold climates and often sited on ice-rich permafrost are required for thermal modelling. Ice-rich permafrost soils with lens ice, wedge ice or other massive ice features are neither homogenous or isotropic and are complicating factors for determination of soil thermal conductivities. Dry densities and moisture contents reported from geotechnical field work and laboratory analysis are typically based on data from a limited number of test pits or bore hole samples. Designers must make their soil property estimates based on the results of the geotechnical investigation.

Thermal conductivity determination can be generally carried out using several varied approaches. In the past many engineers chose Kersten's (1949) results from the late 1940's. Kersten made thermal conductivity measurements on over 1,000 samples of 19 different soil types in the frozen and unfrozen states. In addition to soils from the "lower 48" Kersten also obtained Alaska soils samples which included Northway sand, Fairbanks silt, Chena River gravel and Healy clay. He developed empirical equations to determine thermal conductivities for coarse grain (sands and gravels) and fine grained (silts and clays) soils based on dry densities and moisture contents. It is also noted that his correlations only extend to initial saturation so ice-rich soils are not covered. The advantage of Kersten's approach is simplicity.

Johansen (1975) based his approach on Kersten (1949) data using a normalized thermal conductivity, k_r, concept. He considered the mineralogy of the soil and arrived at relationships for frozen and unfrozen soils where k_r is a function of the degree of saturation. The geometric mean, accounting for the volume fractions of solids, water and ice, was used to determine the saturated thermal conductivity. Johansen also identified quartz content of the soil as a significant factor in the thermal conductivity of the soil solids. Most geotechnical soils labs do not measure quartz content, so typically the designer is left to make an educated guess of its value.

Farouki (1981, 1982) reviewed most of the well-known methods for determining thermal conductivities of frozen and unfrozen soils including Kersten's and Johansen's approaches. He concluded that, generally, Johansen's method provides improved results but it does require knowledge of quartz content.

More recently Cote and Konrad (2005a, 2005b) have published two papers that provide further refinements to Johansen's method. Their work included thermal conductivity testing of granular base course materials as well as a detailed accounting of the soil mineralogy. Their 2005a paper focused on base coarse materials either crushed or natural. A new correlation was developed based on a modified geometric mean approach for dry materials using porosity and fitting parameters with the saturated thermal conductivity calculated as presented by Johansen. Their 2005b paper presents the results of deriving k_r for gravels, sands, silts and clays, and peats. They present thermal conductivities of multiple minerals so solids thermal conductivity can be more accurately calculated if the mineralogy of the soil is known. The dry thermal conductivity is based on soil type including shape effect and porosity. Designers need to be aware that they found an error in the CRREL's translation of Johansen's work for determining thermal conductivity of peats.

For ice-rich permafrost soils Slusarchuk and Watson (1975) carried out thermal conductivity tests on permafrost soil samples. They developed correlations to predict thermal conductivities of frozen and unfrozen ice-rich permafrost soils.

Peat and/or organic layers tend to be a challenge to designers conducting geotechnical thermal modelling. Often times there is limited basic soil characteristic values such as moisture content and dry density from field samples. In many cases the peat/organic layer is not removed during construction and granular fill is placed over it resulting in a compressed layer with the amount it is compressed generally unknown. The 2005b paper by Cote and Konrad provides data and a methodology for estimating the dry thermal conductivity of peat for porosities varying from 0.72 to 0.96.

Unfrozen moisture content in a soil is a function of temperature, soil type and pore water salinity. Andersland and Ladanyi (2004) present parameters for calculating unfrozen moisture content as a function of temperature for soils ranging from gravels to silts and clays. Because unfrozen water content is included in the calculation of the saturated thermal conductivity, frozen thermal conductivity becomes a function of temperature. This is easily accounted for in Johansen's as well as Cote's and Konrad's methods.

It is recommended that designers adopt the Cote and Konrad approach to estimating thermal conductivities of frozen and unfrozen soils.

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