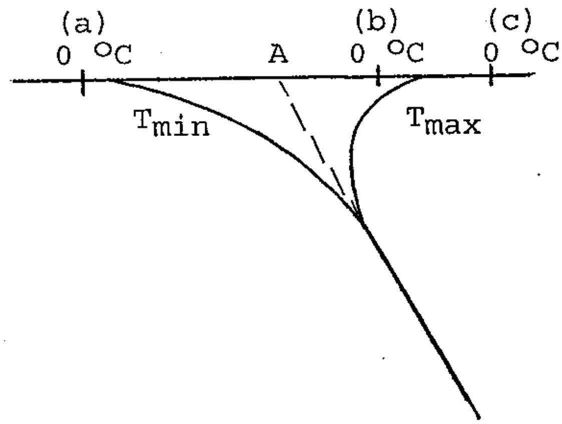
Chapter 1 - PROBLEMS

1.1 Point A in the sketch represents the mean annual ground surface temperature. The curves represent limits of maximum and minimum ground temperatures. Three site locations (relative to the curves) are indicated by points a, b, and c. Which locations are in permafrost regions? Sketch and label the active layer and depth of permafrost (if any) for each site location (a, b, and c).



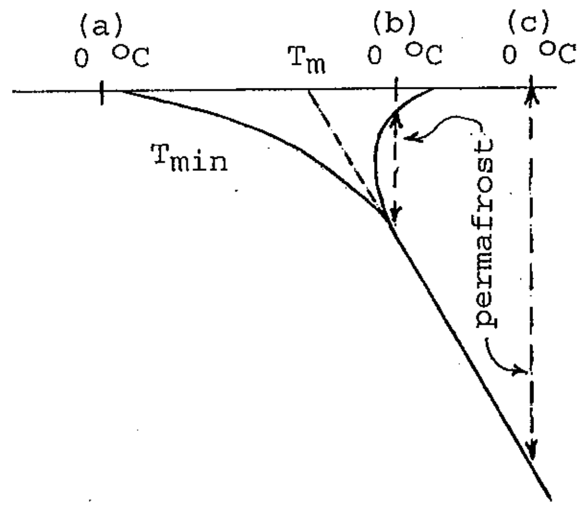
Solution 1.1

Three site locations (points a, b, and c) are indicated relative to a mean annual surface temperature T_m:

Point (a) -- no ground freezing, hence no active layer or permafrost.

Point (b) -- permafrost as indicated on the sketch.

Point (c) -- very thin active layer, it is dependent on temperatures during a warm summer day. Soil will refreeze at night. Permafrost exists to a depth where the temperature approaches 0 °C.



1.2 Annual ground surface temperatures of a frozen sand deposit range from a low of -11 °C to a high of 21 °C. The soil thermal diffusivity equals 0.8×10^{-6} m²/s. Consider the system to be without phase change effects and neglect the geothermal gradient. Calculate the maximum and minimum soil temperatures at a depth of 0.6 m.

Solution 1.2

Given: T = -11 °C to 21 °C, $\alpha = 0.8 \times 10^{-6}$ m²/s, p = 365.25 days, no phase change (no freezing of water to ice with release of latent heat). No geothermal gradient (negligible for a depth of 0.6 m).

Compute: $T_m = [21 + (-11)]\ (1/2) = 5.0$ °C

$A_s = [21 - (-11)]\ (1/2) = 16.0$ °C

1 day x 24 hr/day x 60 min/hr x 60 s/min = 86,400 s/day.

Use Eq. (1.2-4) to compute T_{max} and T_{min}.

$$T = 5.0 \pm 16.0 \exp\left[-0.6 \sqrt{\pi / 0.8\times10^{-6}\ (365.25)(86,400)}\right]$$

$T_{max} = 17.95$ °C $\qquad T_{min} = -7.95$ °C

1.3 The surface temperature of a 2.44 m thick concrete slab varies from +15.5 °C to -40 °C during the year. Determine the maximum temperature at the base of the slab assuming a thermal diffusivity of 0.09 m^2/day for the concrete. Neglect latent heat effects.

Solution 1.3

The average annual surface temperature T_m = [15.5 + (-40)] 1/2 = -12.25 °C and the surface temperature amplitude A_s = 15.5 - (-12.25) = 27.75 °C. The temperature amplitude at the 2.44 m depth (Eq. 1.2-3) equals

$$A_z = A_s \exp -z\sqrt{\frac{\pi}{\alpha \cdot p}} = 27.75 \exp\left[-2.44\sqrt{\frac{\pi}{0.09(365.25)}}\right] = 13.05\ ^{o}C$$

The maximum temperature at the 2.44 m depth is [-12.25 + (13.05)] = 0.80 °C and the minimum T equals (-12.25 - 13.05) = -25.30 °C. The time lag between the maximum temperature at the surface and at the 2.44 m depth is

$$t_z = \frac{z}{2}\sqrt{\frac{p}{\pi\ \alpha}} = \frac{2.44\ m}{2}\sqrt{\frac{365.25\ days}{\pi\ 0.09\ m^2/day}} = 43.85\ days$$

Note that if a small latent heat were accounted for, the time lag would increase and the amplitude at the base of the concrete would decrease.

1.4 Describe the processes involved in formation of an ice-wedge. What factors influence the spacing of these ice-wedges? Explain.

Solution 1.4

Ice wedge formation. Low air temperatures and rapid cooling rates result in large tensile stresses in frozen surface layers. Rupture and crack formation occurs when tensile stresses exceed the frozen soil tensile strength. Water from melting snow fills these cracks, which is followed by freezing and formation of vertical ice veins. As spring temperatures rise the permafrost expands causing horizontal compression and heave of adjacent soil. The following winter low temperatures and thermal contraction again reopen the crack and another increment of ice is added as meltwater enters the crack and freezes. This cycle, operating for many years, results in ice wedges such as those shown in Fig. 1-10.

Ice wedge spacing. Spacing depends on (1) the variation in strength of frozen surface soils and (2) on the width of the stress relief zone adjacent to individual cracks.

1.5 Explain how thermokarst mounds are formed. What initial field conditions are necessary for their development?

Solution 1.5

Formation of thermokarst mounds. A disruption of the permafrost thermal regime, involving a rise in the mean ground surface temperatures, will cause differential melting of patterned ground. The overlying soils will collapse in polygonal patterns with melting of ice wedges resulting in many conical mounds.

1.6 Several basic conditions are required for frost action to develop in highway subgrade soils. (a) What are these conditions? (b) Describe the effects of frost action on a pavement structure relative to the traffic surface, and (c) the pavement support capacity.

Solution 1.6

(a) Basic conditions required for frost action to develop in highway subgrade soils include: (1) a frost susceptible soil; (2) a supply of water (high ground water table); and (3) soil temperatures sufficiently low to cause some of the soil water to freeze.

(b) The heterogenous nature of most soils results in a very non-uniform heave causing an uneven distortion of the traffic surface.

(c) Thawing of ice lenses at a rate faster than melt water can drain leads to high pore water pressures in the subgrade soils and a large decrease in the pavement bearing capacity.

1.7 The heave of a soil upon freezing can be more than is estimated based on the soil water content and the known volume increase during conversion of water to ice. Explain how this is possible.

Solution 1.7

Water will migrate upward through the soil voids by capillary action towards the freezing front, contributing to ice layer growth, until the soil water content below the frozen zone is reduced to about the shrinkage limit. The resulting suction at the frost line also causes water to migrate upward from a lower water table so as to continually replace water lost to ice lense growth during the freezing period. This ice lense growth causes frost heaving.

1.8 What useful aspects of frozen soil are important to the engineer relative to frozen ground support systems? Explain how they might enter into the design of a frozen wall for a deep shaft.

Solution 1.8

Useful aspects of frozen soil include high strength, impervious to water seepage, and high bearing capacity.

Frozen soil strength will determine the required wall thickness needed for support of soils adjacent to a shaft or earth support system and the low permeability will prevent groundwater seepage into the excavation. Soil bearing capacity and support for structural piles also depends on the increased strength.

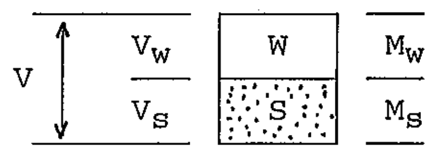
Chapter 2 - Problems

2.1 The water content of a fully saturated silty sand is 30 % and the soil solids have a specific gravity of 2.68. Calculate

(a) the total density before and after freezing.
(b) the volume increase (%) of the soil sample, assuming no water is expelled, all the water is frozen, and the sample has no access to additional water.

Solution 2.1

a) Let $V_w + V_s = 1 \text{ m}^3$



$$\frac{w\,M_s}{\rho_w} + \frac{M_s}{G_s \rho_w} = 1 \text{ m}^3$$

$$\frac{M_s}{\rho_w}\left[w + \frac{1}{G_s}\right] = \frac{M_s}{1.0 \text{ Mg/m}^3}\left[0.3 + \frac{1}{2.68}\right] = 0.6731\,M_s = 1 \text{ m}^3$$

Solve for $M_s = 1.4856$ Mg, then $M_w = w\,M_s = 0.4457$ Mg

and the unfrozen density $\rho = 1.4856 + 0.4457 = 1.9315 \text{ Mg/m}^3$

$V_w = M_w/\rho_w = 0.4457 \text{ m}^3$, recall that water expands 9.07 %

on freezing, hence $V_i = 1.0907\,V_w = 0.4861 \text{ m}^3$

$$\text{Frozen density} = \frac{M_s + M_i}{V_s + V_i} = \frac{1.4856 - 0.4457}{\dfrac{1.4856}{2.68} + 0.4861} = 1.8562 \text{ Mg/m}^3$$

b) $$\text{Volume increase} = \frac{(V_s + V_i) - (V_v + V_s)}{(V_v + V_s)} = \left[\frac{1.0404 - 1.000}{1.0000}\right]$$

Volume increase = 0.0404 (100) = 4.04 %

2.2 A frozen soil sample has a mass of 650 g with an unfrozen water content of 10 %. After thawing and oven drying the sample's mass is reduced to 420 g.

(a) Determine the total water content (w), the ice content ($w - w_u$), and the iceness ratio (i_r).
(b) Assuming full saturation, calculate the void ratio and the degree of ice saturation. The specific gravity of soil solids is 2.68.