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Ground Temperatures

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Information on ground temperatures is necessary for many construction projects. These include the design of airport and road pavements, the determination of the depth at which service pipes to buildings should he laid to avoid freezing, the excavation of foundations, and the design and construction of underground space for buildings. With the growing need for conservation, information on ground temperature is increasingly important for energy calculations such as those for determining heat losses from basements and the possible use of the ground as a source for heat pump applications. Engineers and architects concerned with these problems require a knowledge of the factors that determine ground temperatures as well as an understanding of how these temperatures vary with time and depth from the surface.

This Digest provides general background information on ground temperature measurements available in Canada, the factors affecting ground temperature and the limitations to estimating or calculating these temperatures at a site. Consideration is given only to ground temperatures in regions of seasonal frost south of the permafrost or perennially frozen zone in Canada. It does not deal with temperature in relation to ground freezing problems. This has been the subject of a previous Digest (**CBD 26).**

Measurements of Ground Temperature in Canada

The first known ground temperature measurements in Canada were made at McGill University in 1894. Observations since that time have been sporadic[1] and it wasn't until 1958 that a network of measurement stations was established. Now, Atmospheric Environment Service (A.E.S.), Environment Canada, administers a program of observations, many taken at research establishments of the Department of Agriculture. The observations are taken twice daily at specified depths down to 150 cm (5 ft) or to 300 cm (10 ft) at about sixty stations across Canada.

Daily ground temperature measurements from each station are published regularly in the Monthly Record, the A.E.S. publication containing records of all standard meteorological data such as air temperature, wind and precipitation. Average monthly ground temperatures from all stations have been summarized for the years 1958 to 1972[2].

Various other measurements of ground temperature are available, but most are of limited duration. Ground temperature records have also been maintained for a number of years at several sites in northern Canada by the Division of Building Research as part of a permafrost distribution study.

Because of local variations, available records can give, at best, only a general indication of the range of ground temperatures to be expected at a site. Engineers and architects who require more detailed information are thus forced to make estimates based on an understanding of the many variables that affect ground temperature.

Factors Affecting Ground Temperature

Factors that determine the temperature of the ground can be grouped in three general categories: meteorological, terrain and subsurface variables. Large-scale regional differences in ground temperature are determined primarily by meteorological variables such as solar radiation, air temperature and precipitation. Micro or local variations are caused by differences in terrain, surface characteristics and ground thermal properties.

Meteorological elements, primarily solar radiation and air temperature, influence surface and subsurface temperature by affecting the rate at which heat is transferred to or from the atmosphere and the ground. Solar radiation is probably the single most important factor. Differences in average annual ground temperature between the north and south of Canada are due mainly to the amount of solar energy absorbed at the surface throughout the year. Seasonal and daily changes in solar radiation impose a cyclical variation on both air temperature and ground surface temperature. Other meteorological factors such as wind or rain can cause significant local variations.

Snow is probably the second most important factor affecting ground temperature. This influence is due not only to its well known insulating properties but also to the moisture it provides to the ground during the thaw period. Vegetation can exert a similar insulating effect, protecting the underlying ground from weather extremes that cause high rates of heat transfer to and from the atmosphere. Other terrain features such as slope orientation, can have significant effects. In general, slopes with a southern exposure have a higher average ground temperature than north-facing slopes. There are numerous publications available on the effect of terrain features on ground temperature[3].

The properties of the ground that determine its response to temperature changes at the surface are volumetric heat capacity, C, thermal conductivity, K, latent heat (the heat required to freeze or thaw a unit volume of frozen soil) and water content. The ratio, K/C_v, known as thermal diffusivity, is important in calculating rate of heat flow in the ground.

Water content is a variable property. As heat capacity, thermal conductivity and latent heat depend on it, they also are variable; the larger the water content, the larger the heat capacity, thermal conductivity, and latent heat. The response of the ground to temperature variations is further complicated by the changes that occur on freezing. In addition to the fact that volumetric heat capacity and thermal conductivity of ice differ from those of water, the ground may heave during freezing and settle during thawing.

It is beyond the scope of this Digest to discuss these complex interrelationships. Fortunately, in nature many factors tend to compensate each other so that it is usually possible to use relatively simple formulae to estimate the limits within which soil temperatures will fluctuate.

General Behaviour of Ground Temperature

The principal features of air and ground surface temperature variations can usually be described by an equation of the form

$$T_s = \bar{T} + A \cos \left[\frac{2\pi t}{t_o} \right]$$

where T_s is temperature at a given time; T is the average temperature for the period, involving one or more complete cycles of variation; A is the difference between the maximum and minimum temperatures for the period; t is time, and t_0, time for one complete cycle. If the ground has constant thermal properties, the temperature induced in it by cyclical variation is given by

$$T(x, t) = \bar{T} + A \exp \left[-x\sqrt{\frac{\pi}{\alpha t_o}} \right] \cos \left[\frac{2\pi t}{t_o} - x\sqrt{\frac{\pi}{\alpha t_o}} \right]$$

where x is depth below the surface and a is thermal diffusivity K/C_v.

The amplitude of a temperature variation at the surface is normally about equal to that of the corresponding one for air. Equation 2 shows that it decreases exponentially with distance from the surface at a rate dictated by the time necessary for one complete cycle. This behaviour is shown in Figure 1 for the annual temperature variation. For depths below 5 to 6 m, ground temperatures are essentially constant throughout the year. The average annual ground temperature is practically constant with depth, increasing about 1 C deg per 50 m due to geothermal heat flow from the centre of the earth to the surface.

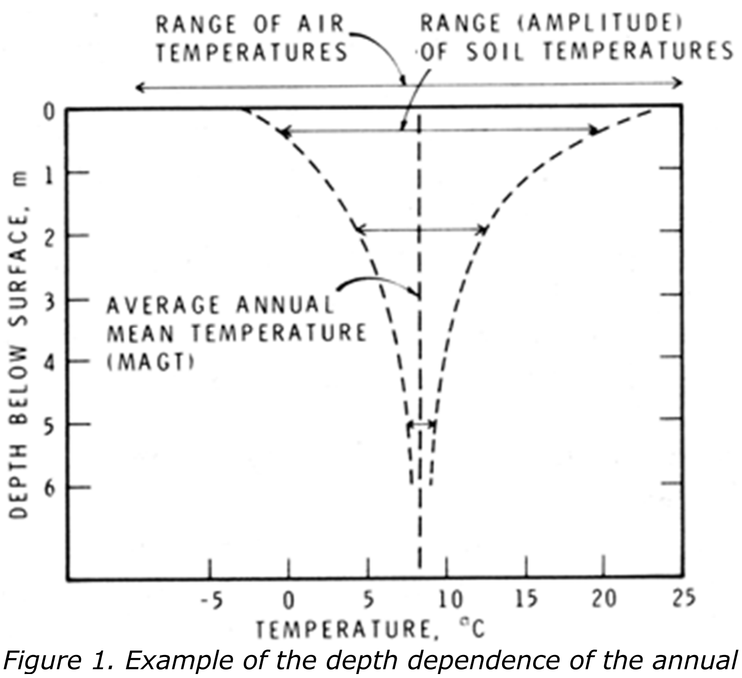

Figure 1. Example of the depth dependence of the annual range of ground temperatures - Ottawa

The temperature of the ground surface remains almost in phase with that of the air. Below the surface, however, the maximum or minimum occurs later than the corresponding values at the surface, the time lag increasing linearly with depth as shown by the cosine term in equation 2. Figure 2 illustrates this behaviour. At a depth of 5 to 6 m the maximum ground temperature occurs about 6 months later than the average maximum temperature of the surface in summer.

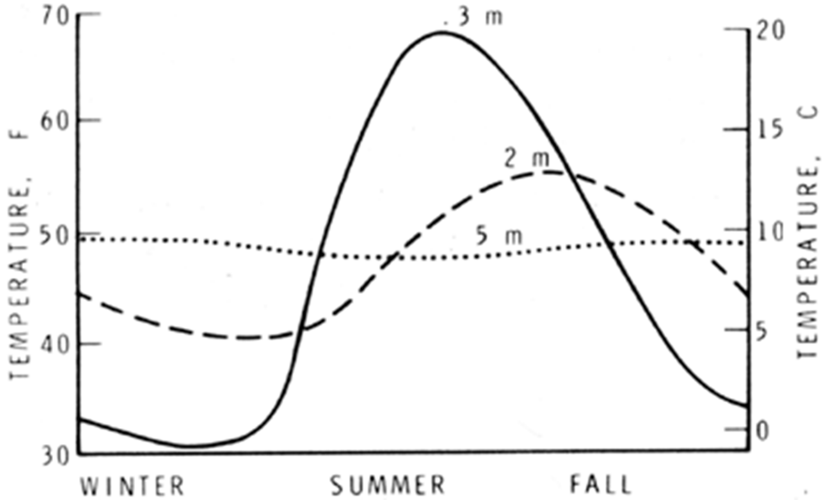

Figure 2 Annual variation of soil temperatures - Ottawa

In addition to an annual cycle, ground temperature undergoes both a daily cycle and a cycle associated with changes in the weather. These variations are confined to the near surface region, daily cycles penetrating about 0.5 m and weather cycles about 1 m below the surface. Daily variations are of some interest with respect to building problems, and of particular interest to agriculturists. They have been the subject of extensive investigation[4].

If the "penetration depth" is defined as the depth at which the amplitude of a temperature variation is reduced to 0.01 of its amplitude at the surface, the depth of penetration of the daily cycle can be calculated to be 7.64 K/C_v; that of the annual wave is 19.1 times this value. Table I gives approximate values for the depth of penetration for a few different types of ground and shows the effect of changes in moisture content.

Table I. Depth of Penetration of Diurnal and Annual Temperature Cycles

	K/C_v cm²/sec	Penetration Depth Day (m)	Penetration Depth Year (m)
Rock	0.020	1.10	20.5
Wet clay	0.015	0.95	18.0
Wet sand	0.010	0.80	14.5
Dry clay	0.002	0.40	6.5
Dry sand	0.001	0.30	4.5

The relation between ground surface temperature and air temperature depends on the characteristics of the surface and on weather, particularly the amount of solar radiation. Normally, the mean annual air temperature (MAAT) is lower than the mean annual ground temperature (MAGT), the difference due mainly to the insulating effect of snow cover, although factors such as evaporation also affect it. The average temperature of a well-kept lawn in summer is appreciably lower than that of a drained surface such as a parking lot because a large percentage of the absorbed solar radiation is dissipated by evaporation or evapotranspiration.

In general, in regions where there is a relatively deep and continuous winter snow cover, the MAGT may exceed the MAAT by as much as 5 C deg; in coastal regions the difference is usually not more than 1 C deg. Information on the differences observed at several locations in Canada is presented in Figure 3. Within each region variations in ground properties and surface characteristics can cause appreciable local variation.

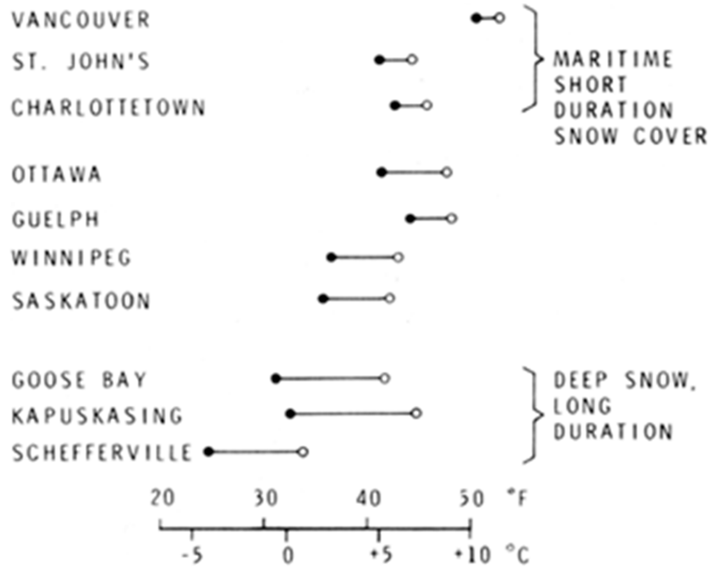

Figure 3. Examples of difference between mean annual ground temperature (°) and mean annual air temperature (·)

Calculating Ground Temperature

Fourier analysis can be used for calculating ground temperatures in some situations for which the temperature variation at the surface cannot be described adequately by equation 1. If the thermal properties of the ground vary with time, even this approach may not be sufficiently accurate or practical, particularly if there is appreciable freezing of water during the period of frost penetration. Programs have therefore been developed for calculating ground temperature by computer for more complicated situations. Computer simulation methods can also be very effective for investigating difficult problems involving layered soil systems, heated basements, artificial skating rinks, snow covers and other features.

For many situations, however, such detail is not necessary. Simple graphical methods may be quite adequate[5]. If ground temperature observations are available for a site, equation 2 can be used to determine the mean annual ground temperature and thermal diffusivity for subsequent calculations.

Modifying Ground Temperature

Almost every man-made change in terrain modifies both surface and sub-surface ground temperatures, although in most cases such modifications are not made for the express purpose of changing the ground thermal regime. Situations can arise, however, where it may be desirable to modify ground temperatures deliberately, for example, to increase the heat capacity of ground for solar heat applications or change ground thermal properties to reduce the rate of heat loss from basements. It should be appreciated that these temperatures can be modified only to a limited extent because man has no appreciable control over climate, which determines values on a regional basis.

In general, ground temperatures can be modified by changing either surface conditions or ground thermal properties. The most obvious method of changing surface condition is to place an insulating layer near or at the surface. The use of insulation under pavements to reduce frost penetration is an example of this type of modification. Increasing the snow cover by the use of snow fences is another example. The thermal capacity of the ground can best be altered by changing its moisture content, for example, by flooding. Various methods of modifying ground temperatures have been applied with some success for agricultural purposes[6], but they have not been used extensively in construction practice.

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