METER
ENVIRONMENT

HOW TO PRODUCE THERMAL DRYOUT CURVES FOR BURIED CABLE APPLICATIONS

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The relationship between water content and soil thermal conductivity or resistivity is often termed a thermal dryout curve (resistivity is the reciprocal of conductivity). The thermal conductivity of a soil depends strongly on water content but also depends on temperature, bulk density, and soil composition. To speak of the thermal conductivity of soil, without specifying the water content, density, temperature, and composition, is meaningless. For a soil in-place, the composition and density are fixed, and the temperature typically varies over a small enough range to have only a small effect on thermal conductivity (unless the soil freezes). The main variable for a soil in place is therefore moisture content. The purpose of the thermal dryout curve is to represent the effect on thermal conductivity of this variability. This application note presents some of the methods which have been used to obtain thermal dryout curves and recommends a simple method, which combines two of them, that will give reliable results.

OPTIONS

Three methods have been used to obtain thermal dryout curves. The first is to model the curve using published relationships for soil thermal properties. The second is to monitor thermal conductivity and mass of a soil sample as it dries from saturation. The third is to mix samples of a soil to water contents over a range and measure conductivity and water content on those samples.

1. **Modeling:** Campbell (1985) and Campbell et al. (1994) have published tested models describing thermal conductivity of soil as a function of water content, temperature, density, and composition. For this method, a dryout curve is produced by determining the composition and density of the test sample and using the model to plot the dryout curve for the desired temperature. This method is very simple and straightforward and requires very little information. Most users of the data, however, are more comfortable if there are some actual measurements of thermal conductivity on their samples to confirm that the calculations are correct. The

model is useful, though, for investigating the effects of compaction, composition, or temperature changes on the behavior of a soil or other thermal backfill material.

2. **Single sample:** For this method, a soil sample, approximately 10 cm diameter and 10 cm deep, is prepared either by coring undisturbed soil or recompacting a soil sample to the desired density for the backfill material (the choice will be based on the intended use of the dryout curve). The sample is saturated with water by placing it in a pan of water around 9 cm deep and allowing it to stand overnight. The TEMPOS TR-3 thermal properties probe, or equivalent, is placed in the sample, and a thermal conductivity reading is taken. The sample is then weighed. Over a period of time, additional conductivity measurements and weightings are made as the sample dries. Finally, the sample is placed in a 105 °C oven to fully dry it, and the final weighing and thermal conductivity measurements are made on the dry sample after it cools to room temperature. From the oven-dry weight and a tare weight, the water contents for all the other measurement times can be computed. The dryout curve is plotted from these data.

This method has the advantage of making all measurements on the same sample without disturbing it, so density stays constant unless the sample shrinks on drying. It has two big disadvantages, though. One is that it takes a long time to obtain the dryout curve. Soil doesn't dry very rapidly unless it is heated, and if it is heated, the high temperatures will strongly affect the conductivity measurements. Also, the thermal conductivity is measured at a point, approximately in the center of the sample. The weight measurement gives the average water content of the sample. Since soils and other porous materials can't be dried uniformly, the average water content will never be equal to the water content at the location of the thermal conductivity measurement. These errors often are not critical because engineers usually only want to know how high and how low the conductivity can go (many only want to know how low it can go). But it still can introduce error, especially in showing where the inflection point of the curve occurs.

3. **Multiple sample:** The typical approach with this method is to start with dry soil, pack it into a sample holder to the desired bulk density, measure its thermal conductivity with the TR-3 needle or equivalent, weigh the sample, and take a small subsample for water content determination. The sample is then dumped back into a larger container which has additional dry soil. Water is added, the sample is mixed, and the process is repeated. 5 to 10 points are quickly and easily obtained. Sample size for the sample holder is not critical, but a 10 cm diameter by 10 cm deep sample holder is convenient.

The advantage of this method is that it is fast and easy. It obviously can't be used on undisturbed cores. The big disadvantage of this method is that it is very difficult to obtain high bulk densities (optimum density) with dry samples. Samples can be compacted to high densities using a hydraulic press, but dry soil can't be compacted using the more conventional drop hammer. Since density is often the most critical factor in thermal backfill materials, this is a big drawback.

COMBINING METHODS

METER recommends a combination of methods 1 and 2. Prepare and saturate a soil core, as in method 2, and measure its weight and thermal conductivity when wet. Then, oven dry the core, cool it to room temperature, and again measure its thermal conductivity and weight. From the weight measurement, compute the density and water content when wet. This set of measurements fixes two points on the drydown curve with direct measurements. The interpolation between these points is done using an equation from Campbell (1985)

$$k\ (Wm^{-1}K^{-1}) = A + B\theta + (k_{dry} - A)(1 - g)$$

where θ is the water content. The constants in the equation are determined from the measurements. K_{dry} is the thermal conductivity of the dry sample. B is computed from

$$B = 2.8\phi_s = 2.8\rho_b/\rho_s$$

where ϕ_s ($m^3 m^{-3}$) is the solids fraction of the soil, ρ_b is the measured bulk density (Mg/m^3) of the sample and ρ_s is the particle density generally assumed to be 2.65 Mg/m^3. The term, g is discussed below but has a value of 1 when the soil is wet, so from Equation 1 and the measurements at saturation

$$A = k_{wet} - B\theta_{wet}$$

where k_{wet} is the thermal conductivity of the wet soil. Making these substitutions into Equation 1 gives

$$k = k_{wet}g + k_{dry}(1 - g) + 2.8\phi_s(\theta - \theta_{wet}g)$$

The function, g goes from a value of 0 for dry soil to 1 for wet soil. If $g = 0$ and $\theta = 0$ are substituted into Equation 4 we get $k = k_{dry}$. If $g = 1$ and $\theta = \theta$ wet are substituted, $k = k_{wet}$. The function, g is computed from

$$g = \frac{1}{1 + \left(\frac{\theta}{\theta}\right)^{-5}}$$

where θ_o is a cutoff water content for liquid return flow in the soil (see Campbell et al. 1994 for details). The function is shown in Figure 1 for sand, loam and clay.

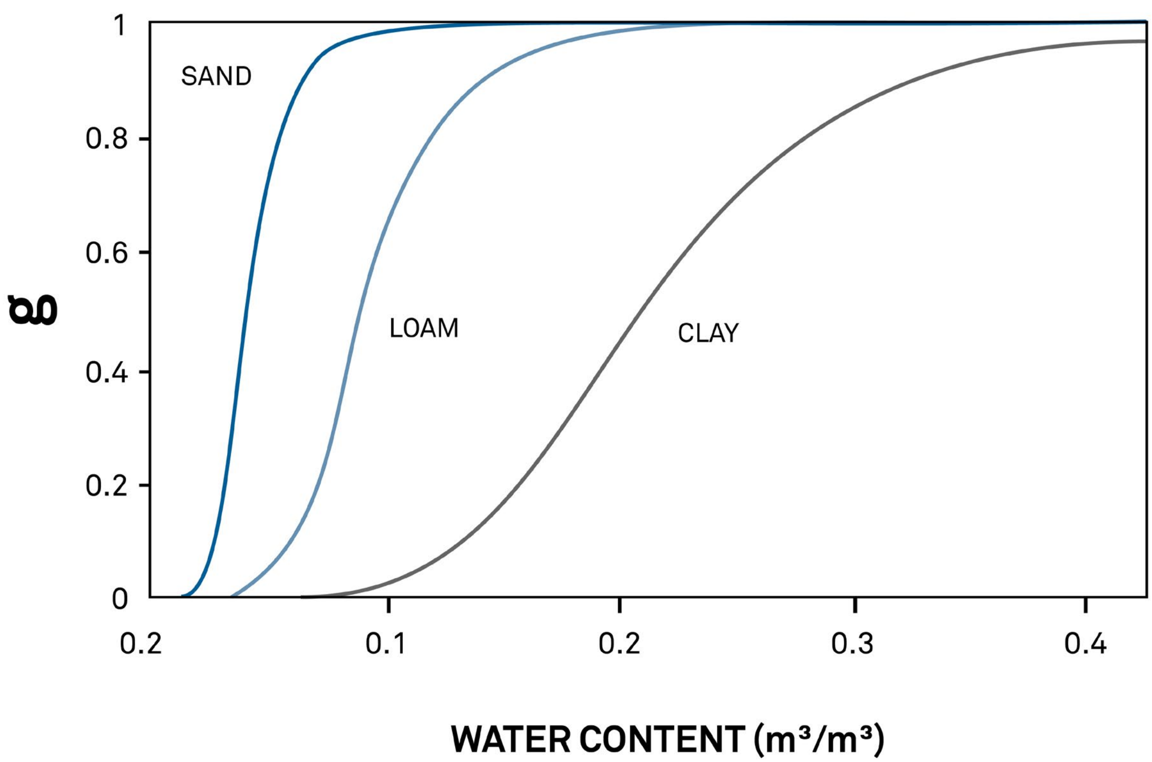

Figure 1. The function '*g*' differs with soil type but ranges from 0 when the soil is dry to 1 when it is wet. This figure shows how it varies for sand, loam, and clay from dry to wet.

The cutoff water content can be estimated from the mass of the clay fraction (m_c) of the sample using the equation

$$\theta_0 + 0.3073 m_c + 0.0334$$

If the clay content is not known, it can be estimated from the soil texture using the following Table 1. Clay content, of course, varies within a textural class. The cutoff water content given by Equation 6 is also shown in Table 1.

Texture	Clay (g/g)	θ_o (m^3/m^3)	w_{ad} (g/g)
Sand	0.03	0.043	0.003
Loamy Sand	0.07	0.055	0.005
Sandy Loam	0.10	0.064	0.015
Sandy Clay Loam	0.27	0.116	0.048
Loam	0.18	0.089	0.035
Sandy Clay	0.40	0.156	0.068
Silt Loam	0.15	0.079	0.033
Silt	0.07	0.055	0.025
Clay Loam	0.34	0.138	0.058
Silty Clay Loam	0.33	0.135	0.055
Silty Clay	0.45	0.172	0.068
Clay	0.60	0.218	0.078

Table 1. If the clay content is not known, it can be estimated from the soil texture using this table (Wad is the gravimetric water content of air dry soil)

NOTES

1. To make a resistivity plot, take the reciprocal of conductivity, as given by Equation 4.

2. The k_{dry} value is for oven-dry soil. This water content is lower than is ever encountered in nature. Its value therefore should not be considered the conductivity of naturally-dry soil. The table above gives approximate values for air-dry water content of soil. Soil in-place will almost always have higher water contents than air dry. One exception might occur if a trench is excavated and the fill allowed to dry for an extended period of time on the soil surface before it is replaced. It would always

be wise to wet the fill around a buried cable, both to increase its density and to increase its conductivity. A little moisture goes a long way in increasing conductivity at the dry end.

3. The high water content matching point does not need to be at saturation. Often, one would like to know the thermal conductivity of a sample packed to maximum density. Once optimum water content for maximum density is determined using standard methods, a sample at the optimum water can be packed and its thermal conductivity determined. This becomes the wet matching point.

4. Swelling clay soils shrink and crack as they dry. Such soils present special problems for the methods outlined here. The wet or saturated measurement can be made as outlined here, but the dry measurement needs to be done in a different way. It is hard to give methods that will work in every situation, but the dry conductivity of these soils can sometimes be measured by taking a clod or ped of the dry soil, carefully drilling a hole for the probe, inserting the probe with adequate thermal grease, and making the measurement.

5. The best results on dry soils will be obtained using the TR-3 needle with a ten-minute read time.

6. The dryout curves using these procedures are for the temperature at which the measurements are made. Temperature has little effect on saturated and dry soil conductivity but affects the conductivity of soil at intermediate water contents considerably. For thermal conductivities at temperatures other than "room" temperature, either detailed models or a full set of measurements must be used. The interpolation method given here would not work.

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