The Effect of Soil Thermal Resistivity (RHO) on Underground Power Cable Installations

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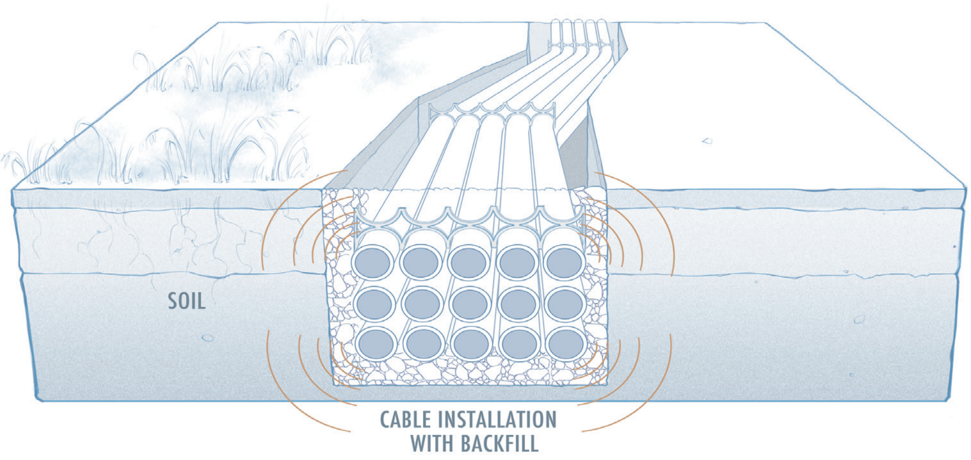

Who would have thought that an electrical power engineer would need to be an expert at soil physics as well. But, increasingly, such knowledge is becoming critical in the design and implementation of underground power transmission and distribution systems. The issues are simple enough. Electricity flowing in a conductor generates heat. A resistance to heat flow between the cable and the ambient environment causes the cable temperature to rise. Moderate increases in temperature are within the range for which the cable was designed, but temperatures above the design temperature shorten cable life. Catastrophic failure occurs when cable temperatures become too high, as was the case in Auckland, NZ in 1998. Since the soil is in the heat flow path between the cable and the ambient environment, and therefore forms part of the thermal resistance, soil thermal properties are an important part of the overall design. The detailed calculations needed to correctly design an underground cable system have been known for over 60 years. The procedures typically used are outlined in Neher and McGrath (1957), and, more recently by the International Electrotechnical Commission (1982). These calculations can be done by hand, but most engineers now use either commercial or home-brew computer programs. The calculations are quite detailed, and are generally based on sound physics or good empiricism, until one gets to the soil. Then the numbers chosen often are almost a shot in the dark. Since, even in a well-designed system, the soil may account for half or more of the total thermal resistance, engineers need to treat that part with as much respect as they do the cables and ducts.

Thermal Resistivity of Soil

Good theories describing thermal resistivity of soil have been around for a long time (de Vries, 1963; Campbell and Norman, 1998). These models are based on dielectric mixing models, and treat the overall resistivity as a weighted parallel combination of the constituent resistivities. Five constituents are important in determining the thermal resistivity of soil. These are quartz, other soil minerals, water, organic matter, and air, in order of increasing resistivity. The actual values for these materials are 0.1, 0.4, 1.7, 4.0, and 40 m C/W. Without knowing anything about the weighting factors for these in an actual soil or fill material, four things should be clear: 1) Air is bad. Fill must be tightly packed to minimize air space, in order to achieve acceptably low thermal resistances. 2) Replacing air with water helps a lot, but water is still not a very good conductor. 3) Organic matter, no matter how wet, will still have a very high resistivity. 4) Fill materials high in quartz will have the lowest resistivity, other things being equal. We will illustrate some of these points with examples.

Density and Thermal Resistivity

Figure 1 shows how important compaction is for achieving acceptably low thermal resistivity in backfill materials. A value often assumed for thermal resistivity of soil in buried cable calculations is 0.9 m C/W. None of the curves in Fig. 1 ever get that low, even at very high density. Typical density for a field soil that can sustain plant growth is around 1.5 Mg/m3. At this density, even the quartz soil has a resistivity more than 4 times the assumed value. Three important observations can be made from Fig. 1. First, organic material is never suitable for dissipating heat from buried cable, no matter how dense. Second, thermal resistivity of dry, granular materials, even when they are compacted to extreme density, is not ideal for cable backfill. Third, the air spaces control the flow of heat, so, even though quartz minerals have 4 times lower resistivity than the loam minerals, the overall resistivity of the two are similar at similar density. It is worth mentioning that arbitrarily high densities are not attainable just by compaction. Uniform sized particles pack to a given maximum density. To attain densities beyond that, without crushing particles, smaller particles are added to the voids between the larger particles. Highest densities are therefore attained by using well-graded materials.

Water Content and Thermal Resistivity

Even though water resistivity is higher than that of soil minerals, it is still much lower than air. If the pore spaces in the soil are filled with water, rather than air, the resistivity decreases. Figure 2 shows the effect of water. The density is around 1.6 Mg/m3, much lower than the highest values in Fig. 1, but with a little water the resistivities are well below 1 m C/W. Now, with more water in the pores, the effect of the quartz is more pronounced. The resistivity of organic soil, though better than when dry, is still much too high to provide reasonable heat dissipation for buried cable.

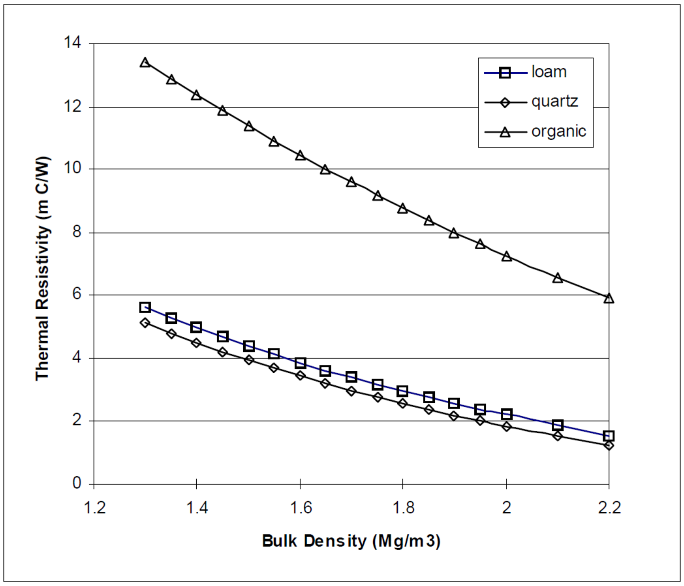

Figure 1 The thermal resistivity of a dry, porous material is strongly dependent on its density.

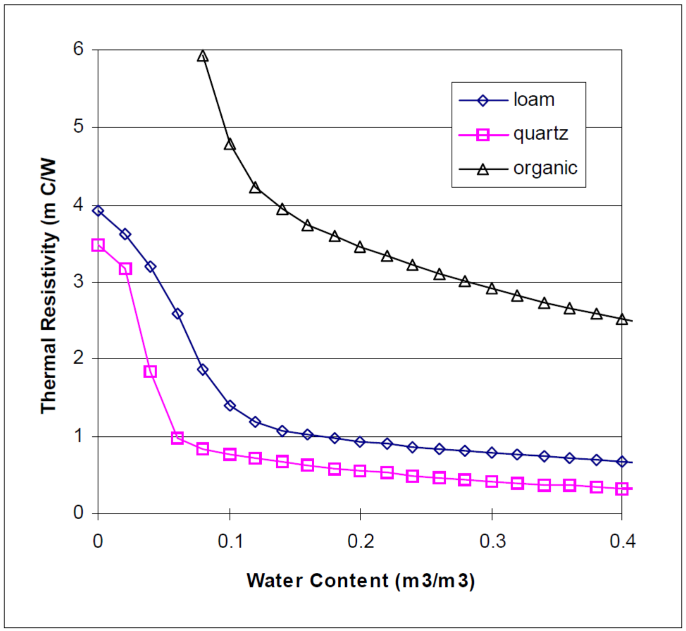

Figure 2 Adding water to a porous material drastically decreases its thermal resistance.

Water content in the field

Since thermal resistivity varies so much with water content, and water content in soil is so variable, it is reasonable to ask what water contents to expect in field soils. Below, and even slightly above a water table the soil is saturated (all pores filled with water). In these situations, one can be certain that resistivities will remain at the lowest values possible for that soil density. Minimum water content in the root zone of growing plants typically ranges from 0.05 m^3/m^3 in sands to 0.1 or 0.15 m^3/m^3 for finer texture soils. These water contents correspond, roughly, to the water contents in Fig. 2 at which resistivity begins to increase dramatically. This is sometimes called the critical water content, and is the water content below which thermally driven vapor flow in a temperature gradient will not be re-supplied by liquid return flow through soil pores. This point is very significant in buried cable design, because, when the soil around the cable becomes this dry, the cable heat will drive the moisture away, drying the soil around the cable and increasing its resistivity. This results in additional heating, which drives away additional moisture. A thermal runaway condition can ensue.

Customized Backfill

Lower dry resistivities than those shown in Fig. 1 can be achieved using especially designed backfill materials. A Fluidized Thermal BackfillTM (FTBTM) can be poured in place. It has a dry resistivity of around 0.75 m C/W, decreasing to below 0.5 m C/W when wet (see http://www.geotherm.net for details).

Measurement

While it is possible to compute thermal properties of soil from physical properties, it is usually easier to measure them directly than to do the computations. Methods are given by ASTM (2008) and IEEE(1992). The accepted method uses a line heat source. Typically a heating wire and a temperature sensor are placed inside a small bore hypodermic needle tube with length around 30 times its diameter. Temperature is monitored while the needle is heated. In this radial heat flow system a steady state is quickly established, and one can plot temperature vs. log time to obtain a straight line relationship. The thermal resistivity is directly proportional to the slope of the line. Several companies offer instruments suitable for either field or laboratory measurements of thermal resistivity, and probes can be left in place to monitor thermal properties after the cable is installed and in use.

Site-specific considerations

In addition to the issues discussed above there are also several site-specific issues that need to be taken into account when designing and implementing underground power cable installations. These include trade-off analysis between depth of installation, cost of installation, and thermal stabilization. The deeper one buries the cables the more stable the thermal environment, especially if shallow water tables and capillary upflow result in relatively moist conditions around the cables. Surface conditions will also impact on the water and energy exchange between the soil and atmosphere and hence the thermal environment around the cables. In cities the surface will more than likely be covered by roads, buildings, parks or gardens, while in rural areas bare soil or vegetative cover will be most common. It is important that surface condition and its impact on the underlying thermal environment be taken into account, and especially any change in surface condition that could result in unwanted consequences. Adding vegetation for example could result in significant soil drying, with potential consequences as discussed earlier.

Clay soils in particular can crack on drying, resulting in development of air gaps around cables, and every effort must be made to avoid this happening. Potential ‘hot spots’ along the cable route (such as zones of well drained sandy soils or vegetated areas that could lead to significant soil drying) should receive particular attention to ensure long-term success of any installation. Additional discussion of some of these issues can be found at http://www.thermalresistivity.com.

Conclusion

There are five important points that the electrical power engineer should take from this short discussion. First, soil and backfill thermal properties must be known for a safe and successful underground power cable installation. One can't safely assume a value of 0.9 m C/W. Second, density and water content play important roles in determining what the thermal resistivity will be. Specify the density of a backfill material, and assure, through design and appropriate management that water content can't get below the critical level. Third, natural soils which support plant growth will always have much higher resistivities than engineered materials because of their lower density and variable, but sometimes low water content. Fourth, engineered backfill materials are available which can assure adequate thermal performance under all conditions. Fifth, measurement of thermal conductivity, both in the field and in the laboratory, is relatively straightforward, and should be part of any cable design and installation project. Finally, there are several site-specific issues such as depth of cable placement, vegetation and soil water management, and avoidance of excessive drying and soil cracking that could lead to air gaps, all of which need to be taken into account when designing and implementing underground power cable installations.

References

ASTM (2008) Standard test method for determination of thermal conductivity of soil and soft rock by thermal needle probe procedure. ASTM 5334-08

Campbell, G. S. and J. M. Norman (1998) An Introduction to Environmental Biophysics. Springer Verlag, New York.

DeVries, D. A. (1963) Thermal properties of soils. in W. R. van Wijk, Physics of Plant Environment John Wiley, New York

IEEE (1992) Guide for soil thermal resistivity measurements. Inst. of Electrical and Electronics Engineers, Inc. New York.

International Electrotechnical Commission (1982) Calculation of continuous current ratings of cables. Publication 287, 2nd ed.

Neher, J. H. and M. H. McGrath. (1957) The calculation of temperature rise and load capability of cable systems. AIEE Transactions on Power Apparatus and Systems. Vol.76

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