CASE REPORT

Case studies on soil heating by cables liners

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ABSTRACT

This work examines various factors related to the heat balance of cable liners to demonstrate the complexity of the soil water and heat balance, and to show how useful it is taking changes in the heat balance into account when planning cable routes. The aim is to achieve optimal technological solutions by keeping effects on the surroundings as small as possible. The following aspects come up: technological issues around cable routes, soil physical basics and ecological aspects around cable routes.

Heat dissipation from the cable into the surrounding soil depends on ambient conditions such as the site's climate, soil properties and usage, and groundwater level. However, the key factor is the thermal conductivity of the surrounding soil. Soil heating also plays an important role in the ecological balance: In the amount of evapotranspiration left for the cultivated plants, and in the distribution and living conditions for the natural vegetation and soil organisms. This means that cable routes need to be assessed and improved not only with regard to the technology used, but also with respect to environmental site conditions.

Key Words: *Cable routes; Soil thermal properties; Buried power cable; Ecological site conditions.*

INTRODUCTION

When planning, constructing and operating underground cable routes, a series of technical and environmental relevant questions need to be asked about the local soil heat balance. When they are in use, underground cables generate heat due to the transport of electric power. To maintain the cables' capacity and extend their lifetime, it is important for this heat to be dissipated as efficiently as possible into the surrounding soil, in order to prevent overheating of the cables. The dissipation heat during peak loads is particularly important. Heat dissipation from the cable into the surrounding soil depends on ambient conditions such as the site's climate, soil properties and usage, and groundwater level. However, the key factor is the thermal conductivity of the surrounding soil. Soil heating also plays an important role in the ecological balance: In the amount of evapotranspiration left for the cultivated plants, and in the distribution and living conditions for the natural vegetation and soil organisms. This means that cable routes need to be assessed and improved not only with regard to the technology used, but also with respect to environmental site conditions [1-3].

This work examines various factors related to the heat balance of cable liners to demonstrate the complexity of the soil water and heat balance, and to show how useful it is taking changes in the heat balance into account when planning cable routes. The aim is to achieve optimal technological solutions by keeping effects on the surroundings as small as possible. The following issues and aspects come up:

Technological issues around cable routes

- How heat emitted by underground cables can be dissipated in different soils; when do critical conductor temperatures of 90°C occur and how can an optimum technological design be achieved? These questions relate to cable cross-sections, cable depths and spacing as well as considerations on the optimization of the cable bed.
- Can an optimization of the technological design help to improve the cable route?

Ecological issues around cable routes

- Questions used in practice to evaluate changes in the water and heat balance of cable routes running across areas used for agriculture and forestry, or under nature conservation areas, including: How do yield and vegetation react on soil heating? Which strategies help to keep potentially damaging effects of the temperature as low as possible?
- How are the living conditions for plants and animals, specifically for soil organisms; are yield depressions to be expected?
- Changes in physical soil properties due to compaction resulting from the construction work and thus potentially influence yield.
- Changes in the groundwater temperature caused by the cable routes

To gain better answers to the above questions on how to design new cable routes and ensure they reliably supply energy, the authors developed new measurement techniques and calculation methods to establish the soil's thermal conductivity, and determined changes in the heat balance of cable routes using numerical models such as the Cable Earth approach, which combines varies numerical sub-models in order to predict water and heat fluxes. These models predict both, the development of the cable temperature and the influences of local conditions along a cable route in order to calculate the resulting cable temperature. This means that the cables' current-carrying capacity with varying local conditions such as soil physical properties and power transients can be predicted or determined better. At the same time, calculation methods can answer questions about soil heating and desiccation, allowing the ecological consequences to be estimated in the context of Environmental Impact Assessments (EIAs).

This short overview offers some basic explanations about soils' heat and water balance, presents site measurements and calculations on cable route heat generation, and reports on case studies from practice [4-8].

Factors affecting soil water and heat balance

The influences of soil properties, local site conditions and climate on a cable route are depicted schematically in Figure 1; the process involves three different, connected levels:

- Water and soil heating regime in the direct vicinity of the cable
- Local conditions: vegetation, soil cover, groundwater depth
- Climate conditions and weather patterns.

The method is capable of analyzing, evaluating and improving the overall system with regard to water and heat transport in the vicinity of the cable as well as predicting effects on soil water balance and crop yield.

Calculation principles

The soil temperature is affected by seasonal and diurnal changes of the soil's surface temperature (caused by incoming and outgoing radiation). The

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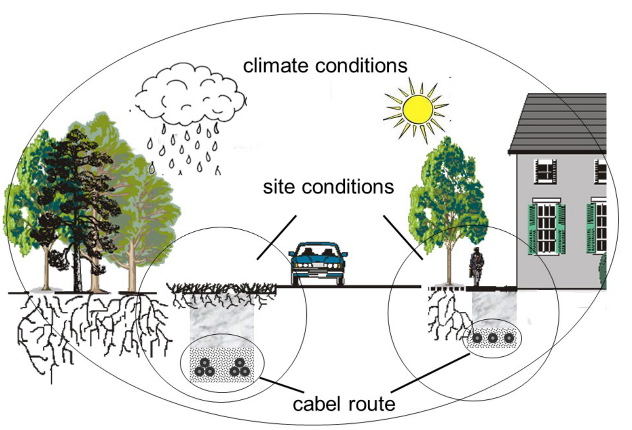

Figure 1) *Environmental factors affecting temperature of cable routes: climate, soil properties, land use*

oscillation extends to a depth of about 10 m at latitudes around 50°. With increasing depth, the phase of the oscillation of the soil temperature shifts and its amplitude becomes smaller [9-12].

It has long been known that the temperature influences the movement of water in the soil. The absolute temperature affects the surface tension of water and thus the soil water potential. Thus, a temperature gradient yields a temperature-induced hydraulic gradient acting additionally to the environmental one. The water flow caused by these hydraulic gradients depends on the hydraulic conductivity of the soil, which is a very steep function of its water content. In rather dry soil, flow of liquid water becomes very small and the main process is the diffusion of water vapor caused by a temperature gradient. In moist soil, the temperature has a far lower effect on water movement than hydraulic gradients induced by water content differences.

The hydraulic and the thermal conductivity and the heat capacity of the soil depend all on its water content. Thus, the water and temperature balance in the soil can only be described using a coupled system of equations. There are two different approaches to the theory behind this system. One is mechanistic, involving the individual flows of water and heat being added together then brought into a coupled system of equations with the conservation of mass and energy. This approach is in line with the Richards equation in isothermal cases, based on a combination of Darcy's law and the conservation of mass. The second approach is based on the equations of thermodynamics. The two approaches ultimately lead to the same equation system. The mechanistic approach is often used in soil physics. The water movement and heat transport are described as follows:

Water transport:

$$\frac{\partial\theta}{\partial\Psi}\frac{C}{\partial t}+\frac{\partial\theta}{\partial T}\frac{\partial T}{\partial t}=\frac{\partial}{\partial x}\left\{(\mathrm{K}_U+D_{\Psi V})\frac{\partial\Psi}{\partial z}+D_{Tv}\frac{\partial T}{\partial z}+K_u\right\}$$

Heat transport:

$$\frac{\partial Q}{\partial\Psi}\frac{\partial\Psi}{\partial t}+\frac{\partial Q}{\partial T}\frac{\partial T}{\partial t}=\frac{\partial}{\partial x}\{(\mathrm{L}(\mathrm{T}_0)\rho_1 q_v+c_1(T-T_0)\rho_1 q_1-\lambda\frac{\partial T}{\partial z}\}$$

with θ:: water content (in liquid and vapor form); Ψ: water tension; T: temperature; Ku: soil water conductivity; D_{Tv}: non-isothermal vapour diffusion coefficient; Q: quantity of energy; L: latent heat of water; ρ_l, qv: water or steam density; c_l, c_v: specific heat capacity of water or steam; λ: thermal conductivity of the soil.

Figure 2 provides a schematic diagram of the transport processes in soil. The transport of water in the pore space includes the water transported in the liquid and vapour phase; in contrast, heat transport is transported in three ways: via the flow of water itself (convection), by transport in the water vapour phase as latent heat, and by thermal conduction [13-20].

The matrix potential gradient and the temperature gradient act as driving gradients i.e., forces which may both be in the same direction or may also be in the opposite direction. In presence of a heat source, which might be a power cable, water vapour flows away from the heat source and condenses at some distance away because of the lower temperatures there, before flowing back to the heat source as liquid water. If it cannot flow back as the soil's hydraulic conductivity is too small, the soil near the heat source dries out. This drying process decreases the thermal conductivity and can cause the cable to overheat [21-23].

A large number of numerical models are available in the literature for calculating the coupled water and heat transport. Rose (1968) developed a numerical model based on the equations proposed by Philip and de Vries (1957). Milly (1982) extended the equations based on the water tension. Benjamin et al. (1990) and Schumacher (1991) wrote two-dimensional models based on Milly's equations. Grunewald (1997) used a three-dimensional model for water and heat transport in buildings. Döll (1996) developed a model based on Milly's equations (1982). A very widely used model is HYDRUS, which is available for 1D and 2D applications.

Considering soil physical properties

Most important physical soil properties are the soil water retention characteristic Θ (Ψ) its hydraulic conductivity function K (Θ), its thermal conductivity λ (Θ) and heat capacity C(Θ).. It is rather time consuming and expensive to measure these properties and it turns out to be not feasible and senseful to do that for thousands of terrain points. To obtain approximate results, transfer functions has been developed, which are based on detailed investigations that allow to estimate the sought functions from easily measurable quantities. Focussing on thermal conductivity, measurements may be carried out by the so-called "thermal needle probe" method which determines thermal conductivity λ [W/mK] for different water contents during a drying process. As an example, Figure 3 shows results for four different types of soil: a sand, a clay, a silt and a peat [24-27].

It is found that soil thermal conductivity of all substrates is very low at low water contents (<5 Vol.%), and soils do not differ greatly. Only at higher

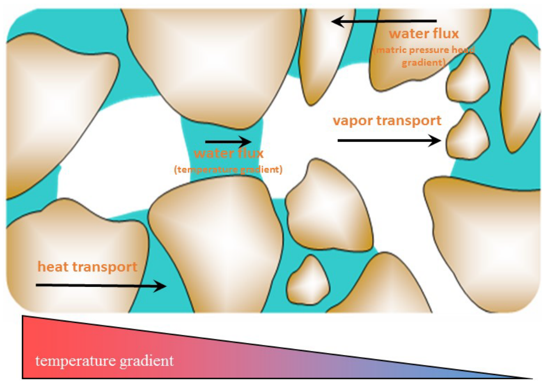

Figure 2) *Principles of water and heat transport in soil*

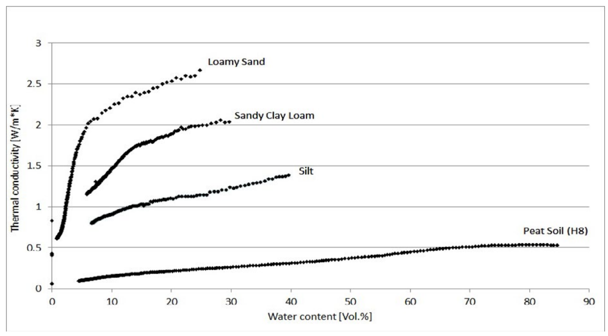

Figure 3) *Thermal conductivity λ [W/mK] of four soils as a function of the water content of a sand (Su_2), a clay, a silt, and a peat soil with a high degree of decomposition (H8), H10= the maximum degree of decomposition according to the German soil classification system (KA5)*

water contents (>10 Vol.%) thermal conductivity rise markedly, reaching the highest values in sand, followed by clay and silt. Turfs, on the other hand, act as an insulator. It shows only a low thermal conductivity across the entire range of water contents.

To achieve stable thermal conditions in the soil and improve the thermal conductivity of the cable bed, additives are often added to the soil around the cable, or fluid backfill material is used. So far, soil physics and ecology have come up with few insights into the long-term effect these materials might have in the unsaturated zone.

To estimate the thermal conductivity function of a given soil from data on its grain size distribution and its bulk density, a large number of so called pedotransfer functions are in use. They may be divided into physical based models and empirical approaches The deVries (1963) method is a physical based method and calculates soil thermal conductivity from a volume-based weighted mean over all soil constituents. To take into account the shape of soil mineral particles, an empirical parameter must be introduced. Above a certain threshold, water is assumed to be continuous, beneath of that threshold, soil air is regarded to be continuous. For further details readers are referred to Döll (1996) and her computer code “SUMMIT” to simulate the flow of heat and water beneath mineral liners of waste disposals.

Brakelmann (1984) developed an empirical formula to estimate soil thermal conductivity based upon bulk density and water content. His method has been used successfully for the planning of buried power cables:

$$\lambda = \lambda_w^{\phi}\lambda_b^{(1-\phi)}exp(-3.08?(1-S)^2)$$

With

λ_b thermal conductivity of soil mineral solids, approximated by:

λb=0.0812*sand%+0.054*silt%+0.02*clay%

ρ_p particle density, approximated by

$$\rho_p = 0.0263*sand\% + 0.0265*silt\% + 0.028*clay\%$$

S $saturation\ degree, S = \theta / \Phi$

Markert et al. (2017) improved an earlier approach developed by Lu and derived equations valid for three different texture classes containing eight parameters each.

$$\lambda_{dry} = p_1 + p_2\Phi$$

$$\Phi = 1 - \rho_b / \rho_p$$

$$\delta = p_3 f_{clay} + p_4$$

$$\beta = p_5 f_{sand} + p_6\rho_b + p_7\rho_b f_{sand} + p_8$$

$$\lambda(\theta) = exp\left(\beta - \theta^{-\delta}\right) + \lambda_{dry}$$

The three textural groups are defined by the content of silt and clay. For details on these methods readers are referred to the literature cited. The best pedotransfer functions predict the soil thermal conductivity typically with a RMSE (root mean square error) between 0.27 und 0.38 Wm-1K-1 (Wessolek & Bohne, 2022).

Case studies on the temperature in the vicinity of the cable route

To provide an example, we present selected results from experimental sites. To assess the effects which cable routes have on the environment, we used various numerical models which are coupled to one another across different scales, for example via defined interfaces or boundary conditions (e.g., via the soil temperature at a defined soil depth). Figure 4 shows exemplarily a route model (Cable Earth) coupled with a location model (HYDRUS). As a result, temperatures and water contents can be calculated for cables operated under various site conditions, along with evaporation, plant water stress, yield and leaching .

First, a case study for Lindenberg, south of Berlin, Germany, done in a master thesis of Leithold (2018) is presented soil temperatures of a silty soil, cultivated with maize for two site conditions: (i) with and (ii) without the influence of a cable liner in 150cm depth. Calculations have been done for three different climate years: (a) a wet year with high precipitation 780 mm/a, (b) a normal, i.e., long-term average year with 556 mm/a precipitation, and a dry year with 489 mm/a precipitation (Figure 5).

Highest i.e., maximum soil temperatures in the subsoil (100 cm depth) occur in late summer (August), when the heat wave caused by the radiation of the atmospheric conditions reaches the subsoil.

It’s remarkable to see in the topsoil that differences between the three years are relatively small, soil temperature in the topsoil reaches 15-18 degree Celsius. In normal years and wet years, soil heating by cable route leads to a temperature increase of 4K to 8 K in the topsoil and up to 15K in the subsoil. In very dry years, such as in 2015/16, temperature increase is less pronounced in the topsoil, because heat conductance is strongly reduced by low soil moisture contents. However, in the subsoil soil temperature might increase by 15 K to 20K.

In the next case study, we examined the development of the subterranean temperature field. An entire cable route was considered as part of an aquifer. Assuming that in this situation there is an ambient cable temperature of 50°C, a groundwater flow of one meter per day, and a groundwater temperature of 10°C. HYDRUS 2D and the MODFLOW model simulates the new temperature fields as shown in Figure 6.

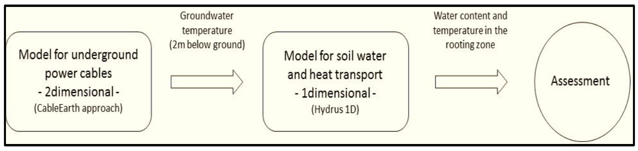

Figure. 4) *Numerical models used for the assessment of cables routes*

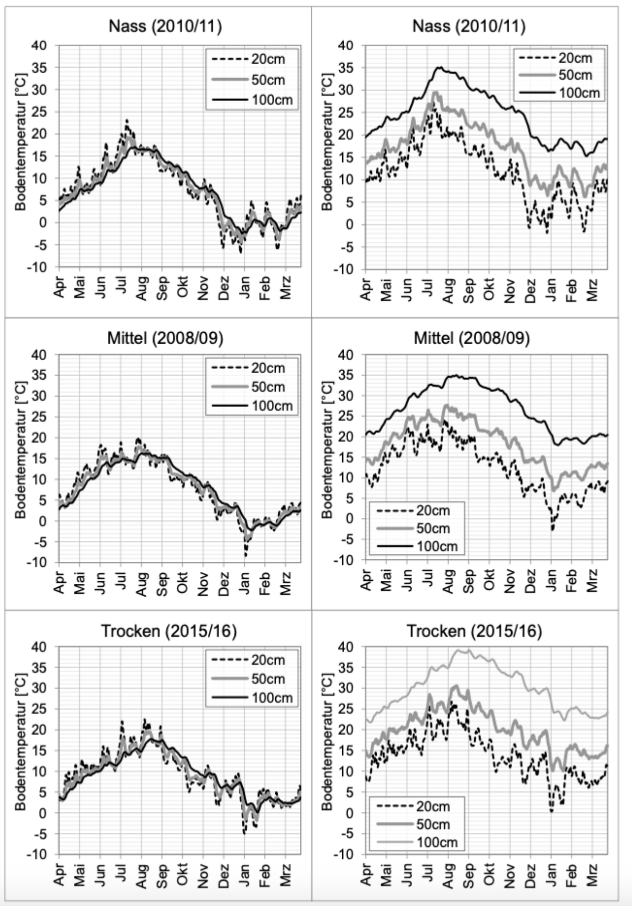

Figure 5)*Case studies of soil temperatures in 20 cm, 50 cm, and 100 cm depth for a maize cultivated silty soil without (left) and with the influence of a cable route (right side) for a “wet year” (2010/11), a “medium year” (2008/09) and a “dry” year (2015/16), results according to Leithold (2018)*

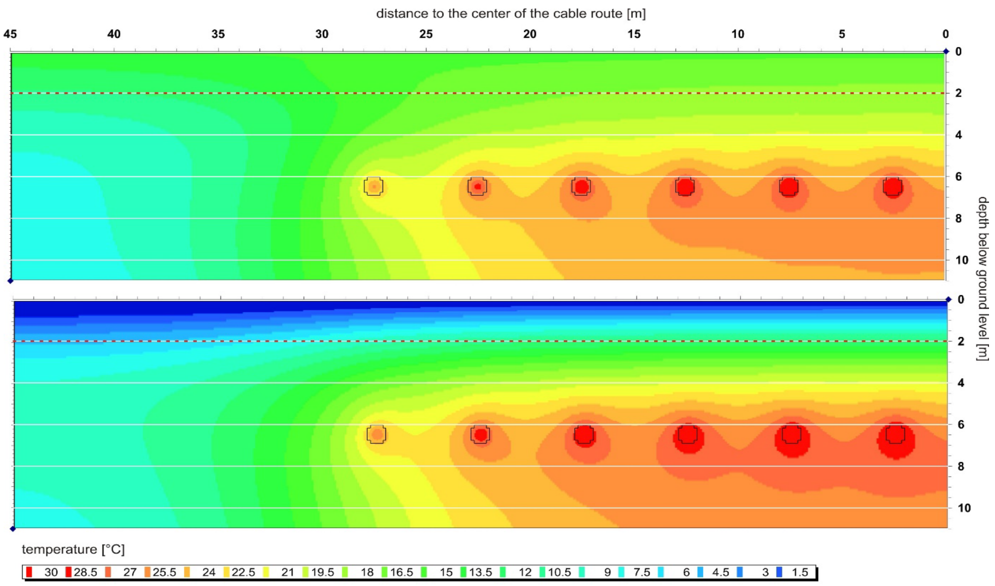

Figure 6) *The development of temperature fields (summer on top, winter on bottom) of a vertical-plane cross-section for a complex cable system of six singe liners. The groundwater flows from left to right by 1m per day. The heat generated by the cables is transmitted laterally by groundwater flow*

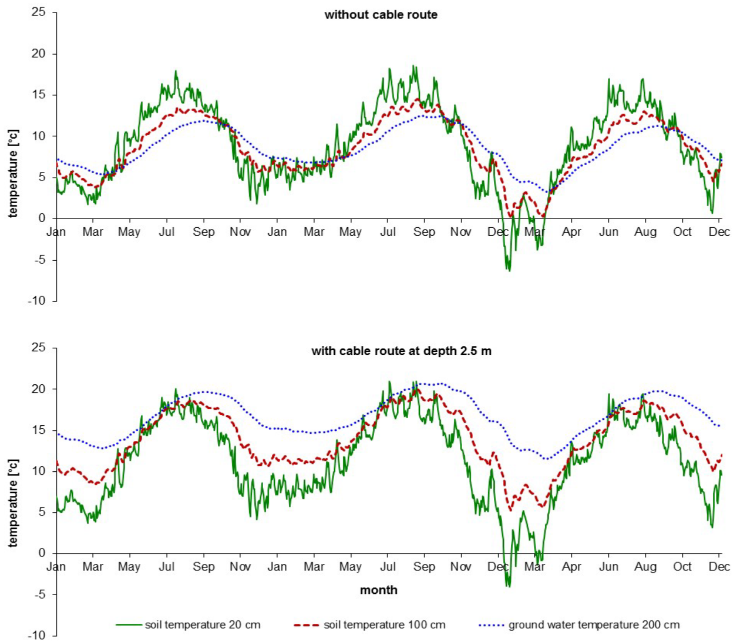

Figure 7) *Modelled groundwater and soil temperatures at different depths unaffected (top) and affected (bottom) by cables buried at a depth of 5m, over a three years period*

In order to estimate influences on the environment, it is therefore necessary to include the wider surroundings of the cable in the investigations. The depicted temperature expansion is calculated based on conservative assumptions of stationary conditions, i.e., not taking into account additional cooling effects resulting from extremely cold periods of frost or from very cold ground water penetrating from the surrounding area or from nearby trenches. This would cause the temperature fields to cool down repeatedly, and stationary conditions could only occur rarely. Nevertheless, these scenarios provide us with a much better imagination to which distances and extend soil heating can be expected around the cable route and of the temperature patterns in the subsoil and aquifer.

Simulation calculations have further shown that heat conduction without convection results in a rapid distribution of relatively small amounts of heat. When heat is dissipated through convection along with flowing groundwater, very large amounts of heat are transported. However, this is a very slow process.

In a second step, moving away from the overall system, the temperature change in the rooted soil can be predicted along individual parts of the route, as illustrated in Figure 7.

CONCLUSION

In order to determine the necessary heat dissipation from buried power cables and the influence of the energy introduced on the soil, the physical processes of heat propagation in the soil must be taken into account. The dissipation of heat occurs to a large extent by convection of latent heat during vapor transport. In practice, the physical soil properties can be represented by transfer functions, but easily applicable methods for simulating the temperature fields in the soil are only at the beginning of their development. The complicated processes of water and heat transport in the vicinity of line sources can be well represented by simulation models, but these models require a great deal of data and experience in their application. Development of these models with a view to easier applicability has been tackled only sporadically so far.

Other interesting areas of application concern urban spaces, which usually offer little scope for the construction of new cable routes. Here, models like cable earth, allow the cable temperatures to be calculated during power transfer in existing routes. In addition, the method makes it possible to specifically identify critical transmission situations which can occur, for example, when cables cross district heating pipes. A last conclusion is the urgent need of field studies, i.e., long-term observations on cable routes, because most results presented here are numerical studies. These have to be validated. We also need real data i.e., information in view of understanding complex ecological processes that cannot be predicted easily, such as nitrogen turnover, biological shifts and chemical reactions in the soil solution.

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