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Efficiency of Buried Cables Depending on Hydrogeological and Geothermal Properties of Trench Fill Materials

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ABSTRACT

Small power plants using geothermal and other forms of renewable energy will cause a decentralization of electric power production and this requires extensive changes of the electric supply network. Considerable amounts of heat are emitted by underground power cables under electrical current flow. The maximum current rating of the cables is limited by the maximum conductor temperature. The dimensioning of the distances between cables to avoid mutual heating, as well as the maximum current load relies on standardized values. These values are considered as partly conservative limits, because any thermal overload can significantly reduce the lifespan of the cables and increase operation costs. Each form of grid optimization is of considerable economic interest. Medium and low voltage cables are usually laid at a depth of 60 to 80 cm. In order to optimize the maximum load, precise knowledge of the thermophysical and hydraulic properties and their interrelation in the partially saturated surrounding unconsolidated rocks is required. Within the research project several parts can be distinguished. Laboratory tests are conducted on unconsolidated rocks from the project area in Bavaria (Germany), determining the relevant hydrogeological and thermophysical properties and compiling the data in a geographic information system (GIS). In addition, field investigations on an underground cable test field in which the cables are embedded in representative (well-defined) soils and thermally enhanced bedding materials are conducted, as well as monitoring of real cable routes. The results of all tests are used for the calculation of heat flow using the finite elemente method and analytical methods. The results can be used to optimize the design of electrical cable routes as well as the design of shallow geothermal installations.

1. INTRODUCTION

The use of renewable energy sources is increasing. Small power plants using geothermal and other forms of renewable energy cause a decentralization of electric power production and this requires extensive changes to the electric supply network. Power lines previously serving electricity consumers may reverse the direction of the current flow incorporating decentralized electricity producers. Considerable amounts of heat are emitted by underground power cables under electrical current flow. The maximum current rating of the cables is limited by their maximum conductor temperature. Medium and low voltage cables are usually laid at a depth of 60 to 80 cm. In order to optimize the distances between cables, precise knowledge of the thermophysical and hydraulic properties and their interrelation in the partially saturated surrounding unconsolidated rocks is required.

2. SOIL SAMPLING AND LABORATORY TESTS

Representative soil samples from the project area will be obtained and characterized in laboratory tests. Sandy soils will be tested with the columnar test device (Fig. 1, A.1 and A.2) containing frequency domain reflectometry (FDR) sensors which are calibrated after Starr and Paltineanu (2002) at various levels determining the water content, tensiometers for measuring capillary tension and a line source device after Blackwell (1954) for measuring the thermal conductivity simultaneously. The soil samples in the column can be irrigated from both top and bottom. The results will show the thermal conductivity as a function of capillary tension and water content.

Additionally an evaporation test after Schindler (1980) and Schindler et al. (2010) of the type HYPROP® was equipped with a thermal conductivity sensor (Fig. 1, B.1 and B.2). This experimental setup allows the combined determination of thermophysical and hydraulic properties under conditions of desorption in a comparatively short time (Sass and Stegner, 2012). For the characterization, calculation and modeling of thermal processes in soils thermal conductivity is the most important parameter. Thermal resistivity, as it is generally used in electrical engineering is the reciprocal value of the thermal conductivity.

Thermal conductivity of soils largely depends on the degree of water saturation. As the heat dissipated by a

buried cable induces convective processes both in the soil-water and soil–air. Precise knowledge of the hydraulic and thermal characteristics are important to allow predictions on maximum allowable current loads.

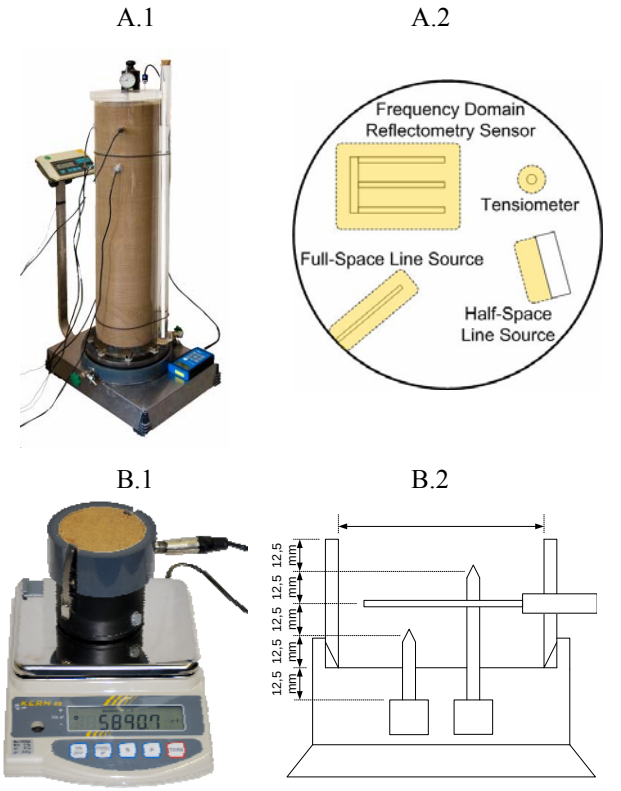


Figure 1: A.1: Columnar test with 1 m height and 22 cm diameter. A.2: Typical arrangement of probes at one level within the column. Line source device for measuring the thermal conductivity, tensiometer for measuring capillary tension and frequency domain reflectometry sensor for the measurement of water saturation. The corresponding measuring area is colored yellow. B.1: Evaporation test of type HYPROP® with integrated full-space line source for thermal conductivity measurement. B.2: Sketch of the experimental setup.

Thermal conductivity of soils is controlled by the degree of water saturation. The thermal conductivity as a function of water saturation of soils is not a linear function. The soil samples examined for this project show a behavior, as illustrated in Fig. 2. In the course of the project clays and silts will be examined which can be regarded as representative for the area serviced by E.ON Bayern.

The combined presentation of the measurement results of several sandy soil samples illustrates the soil specific and material dependence of thermal conductivity. The examined sand samples feature thermal conductivities between 1.5 and 2.8 $Wm^{-1}K^{-1}$ when fully saturated. A precise classification of soil types allows for a more exact prediction of thermal conductivities, instead of relying on approximate reference values.

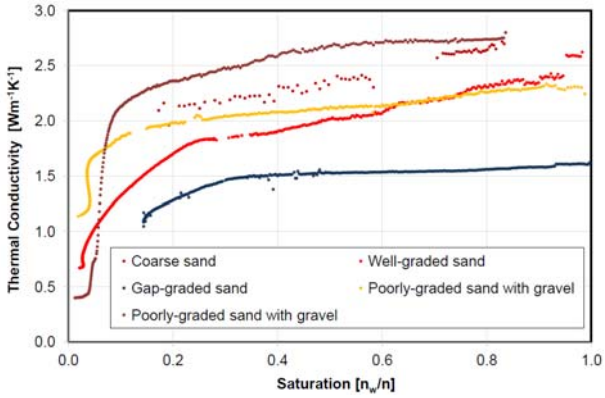


Figure 2: Laboratory study of the thermal conductivity of various sands as a function of saturation

Soil water distribution in a defined pore space at different water contents is reflected in the water retention curve. The aim is to find suitable functions in order to adjust the water retention curve through the simultaneous determination of the characteristic values in the laboratory tests. These functions also pose as the basis for the subsequent FEM modeling.

The measuring methods applied in this project are the subject of ongoing research. The data collected is continuously applied to validate the analytical models predicting thermal and hydraulic variations in soils. The soils to be examined in the test field as well as other representative soils of the project area are currently described for their thermophysical and pedological characteristics. Also investigations and designing of embedding materials for cables based on liquid soils and hydraulic hardening building materials is conducted.

3. NUMERICAL AND ANALYTICAL CALCULATIONS

The measured values of thermal conductivity, capillary tension and water content will be converted into continuous functions using curve fitting methods. These functions form the basis for the coupled thermal and hydraulic FEM modeling. Currently various functions common in hydraulic modeling are examined, e.g. if the capillary tension / saturation relationship after van Genuchten (1980) is transferrable to the capillary tension / thermal conductivity relationship.

A preliminary function (eq. 1) representing the capillary tension / thermal conductivity relationship was developed based on the van Genuchten function. Fig. 3 illustrates the resulting continuous function generated from measurements on a poorly-sorted medium-grained sand obtained in the columnar test after chapter 2.

$$\lambda(\psi) = \lambda_r + \frac{(\lambda_s - \lambda_r)}{\left[1 + (\alpha_\lambda \cdot |\psi|)^{n_\lambda}\right]^{m_\lambda}} \qquad (1)$$

With:

$$m_\lambda = 1 - n_\lambda^{-1} \quad (2)$$

Where is:

λ_r	[$Wm^{-1}K^{-1}$]	Ovendry thermal conductivity
λ_s	[$Wm^{-1}K^{-1}$]	Saturated thermal conductivity
α_λ	[m^{-1}]	Scaling parameter
n_λ	[-]	Inclination parameter

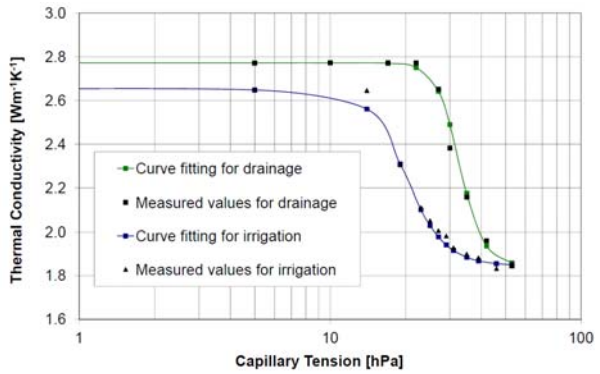


Figure 3: Capillary tension and thermal conductivity of a poorly sorted medium-grained sand obtained by a columnar test.

The thermophysical and geomechanical properties of this medium-grained sand have been precisely determined in previous studies. The results of the calculations were incorporated into the design of the test field. Further validation of FEM modeling of the temperature distribution around the underground cables will be conducted by comparison with the measured values from the test field.

4. FIELD INVESTIGATIONS

The overall dimension of the test field (Fig. 5) is 14 m by 6 m, divided into four sections of 3.5 m length. Various cable configurations according to the german standards DIN will be embedded in the field at depths between 0.6 m and 0.8 m. The specifications of the medium-voltage cables buried in the test field are NA2X(F)2Y 1x150 RE/25 mm² and N2XS(F)2Y 1x400 RM/35 mm², the low-voltage cables' specifications are NAY2Y-J 4x150 se.

The individual sections are hydraulically independent, as they are segregated by an impermeable plastic layer. In fields one and four the naturally occurring sand on site will be replaced by well-defined clay and silt down to a depth of 2.5 m. In field two the naturally occurring sand will remain and field three will contain thermally enhanced bedding material.

Several high power transformers allow the buried cables to be energized in multible configurations at different electric current loads. The individual configuration of medium and low voltage cables (Fig. 5, I and IV) allows the measurement of the thermal and hydraulic influence of a single cable on the surrounding soil. The cable configurations II and III can each be energized in any desired configuration to determine the mutual heating of cables in common cable configurations possible in a single trench.

The variations of the thermal and hydraulic conditions at the test field are monitored by several types of sensors. 8 tensiometers measure the capillary tension; 20 FDR sensors measure the water content and 80 Pt100 thermometers measure the temperature. Additionally thermal variations are recorded by optic fiber cables applying the distributed temperature sensing (DTS) method which are laid out and buried in loops.

The data will be correlated with weather data, i.e. temperature, precipitation and solar radiation. Afterwards they will be validated in coupled thermal-hydraulic numerical models. The measurements will be conducted continuously during the first project phase for one hydrological year.

In December of 2012 the fields designated to contain the clay and silt replacing the naturally occurring sand were filled to the level at which the cables will be buried, later (Fig. 4).



Figure 4: Left: Bottom of test field at 2.5 m depth before being filled up with clay. A fiber optic cable is laid out in four loops on the surrounding sand for detailed temperature determination. Right: Filled with compacted clay up to 1.2 m depth. 16 loops of fiber optic cable are laid out at this level, as well as three Pt100 temperature sensors. To prevent electromagnetic induction, the sensor cables are shielded by aluminum pipes (white).

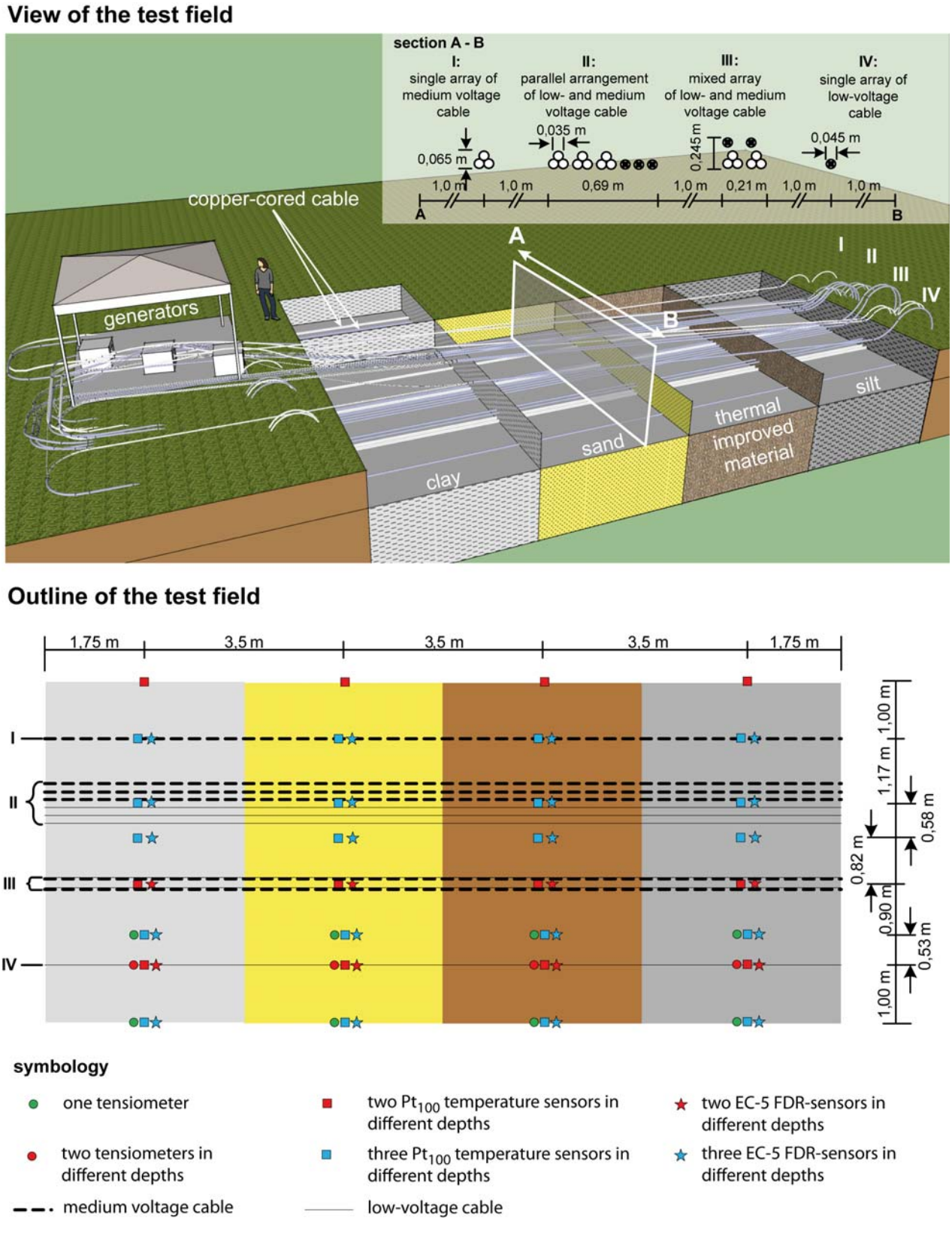


Figure 5: Test field for buried cables with the locations of the installed instrumentation. The cables are buried in accordance with the German standards DIN.

5. COMPILATION OF RESULTS IN GIS

In order to clearly arrange and present the data obtained in the field in their spatial context, the pedological map of Bavaria is geo-referenced in ArcGIS. Every soil unit is digitized and locations where samples were obtained are assigned an individual identifier (ID). The data obtained from the soil samples is then correlated with the respective soil unit through this ID.

It will be possible to generate specifically themed maps, incorporating the results both from the laboratory and the field, to aid in the planning of cable routes by indicating variations of thermal conductivity of soils through color scales. This provides a large-scale overview, which cannot replace individual evaluation of small-scale, possibly anthropogenic variations or greater natural variations. An identification tool will provide access to additional information on the characteristics of the respective soil unit and local conditions (Fig. 6).



Figure 6: Excerpt from the digitized soil map of Bavaria with opened window showing additional information.

6. CONCLUSIONS AND OUTLOOK

Laboratory tests are conducted on unconsolidated rocks from the project area in Bavaria (Germany), determining the relevant h and thermophysical properties and compiling the data in a geographic information system (GIS).

For this purpose the influence of the following parameters on temperature distribution around the buried cables will be quantified in the coming years:

- The local weather conditions and surface temperature.
- Thermal soil properties, e.g. thermal conductivity, thermal diffusivity and heat capacity.
- Hydraulic properties of the partially saturated, unconsolidated rock, e.g. the relationship of capillary tension and saturation (water retention curve), as well as the partially saturated hydraulic conductivity.
- The influence of hydraulic characteristics on the thermophysical properties.
- Thermally enhanced bedding materials.

In addition, field investigations on an underground cable test field in which the cables are embedded in representative soils and thermally enhanced bedding materials are conducted, as well as monitoring of real cable projects. The results of all tests are used for the calculation of heat flow using the finite elemente method and analytical methods for the dimensioning of buried cable routes.

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