SuedLink: thermal design of underground high voltage cable routes

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ABSTRACT: The 700 km SuedLink underground power line will transmit renewable energy between northern and southern Germany using extra-high voltage direct current (HVDC) cables. As one of the first large-scale projects of its kind, SuedLink plays a pivotal role in Germany's clean energy transition and sets a global benchmark for the thermal design of underground cables. The thermal conductivity of soils is a critical parameter for thermal design, as managing thermal interactions is essential to prevent overheating, reduce cable spacing, and minimise costs and environmental impact. This is why, in the absence of internationally recognised standards, a process for testing soil thermal conductivity was developed as part of the SuedLink project. Similarly, a manual for interpreting the thermal conductivity test results and a thermal design guide were also developed. These innovations support efficient and reliable planning of underground cables. This paper provides an overview of the thermal conductivity testing and thermal design processes employed for SuedLink, highlighting key lessons learned and their relevance to future projects worldwide.

1 INTRODUCTION

The approximately 700 km long SuedLink underground power line will transmit renewable energies between windy northern Germany and where it is needed in the industrial zones of southern Germany. The 4-GW transmission capacity of SuedLink, at 525 kV, means that approximately 10 million households can be powered by the energy flowing through its cables.

For the most part the SuedLink power line consists of four extra high voltage direct current (HVDC) cables that are laid next to each other. These are installed either by means of open excavations or trenchless construction techniques such as horizontal directional drilling (HDD) or Microtunneling.

As with any conductor, these cables emit heat as electrical energy flows through them, which has to be dissipated into the surrounding ground. To ensure functionality and prevent overheating, it is essential to correctly dimension the cable spacing and select appropriate backfill materials.

The investigation of the thermal conductivity of soils in underground cable projects has historically been overlooked, as no standardised process existed. Consequently, results often exhibited significant variability. To account for this uncertainty, extremely conservative assumptions were typically made regarding the thermal properties of soils surrounding underground cables.

This is why accurate determination of the soil's thermal conductivity (λ) is critical, as it enables efficient dimensioning of cable spacing and backfill materials, leading to cost savings and a reduced environmental impact.

Currently there is no internationally recognised standard for determining the thermal conductivity of soils – only the configuration of the needle probe and the subsequent measurement to determine the thermal conductivity are described in standards ASTM D5334:22a and IEEE Std 442-2017. However, experience in recent decades has often shown that deficiencies in the execution of tests also contribute to significant errors. This is why a project specification was developed that also detailed the processes of sampling, sample transport and measuring thermal conductivity across various water contents. This project specification has been adopted by the four transmission system operators in Germany and is currently being adapted to form a German national standard.

The methodology stands out for its ability to provide reproducible thermal conductivity measurements across the entire water content spectrum of a soil. This is particularly significant, as thermal conductivity depends not only on density and mineralogy but also on water content. Furthermore, the highly efficient testing setup facilitates large-scale application, as demonstrated by the completion of over 6,000 tests for the SuedLink project.

As per standard design practises (Cigré 1992b, IEC 60287-1-1, IEC 60853-3, DIN VDE 0276-1000) underground cables are dimensioned on the basis of the two-zone model. This is why once the thermal conductivity of the soils has been determined from the oven-dried state to the near-saturated state, further interpretation is required to derive the characteristic thermal conductivities. These correspond to the soil's water content at two key conditions: the driest natural state of the soil (unaffected by the cable) and the cable-induced drying state. This pair of characteristic thermal conductivities (λ-Pairs) is required for performing thermal design calculations based on the two-zone model (Cigré 1992a).

The λ-Pairs are applied to the ground layers within the geological model to develop a thermal ground model. This model is a critical tool for identifying sections that govern the thermal design of the underground HVDC cables.

The primary outcomes of the thermal design include dimensioning the cable spacing and selecting appropriate backfill materials.

As a result of the extensive thermal conductivity testing conducted on soil samples during the SuedLink project, the processes of testing, interpreting the results, and performing the thermal design have been thoroughly established. This has provided valuable experience and important lessons learned throughout the project.

This paper outlines the processes for testing soil thermal conductivity, interpreting results to create thermal ground models, and conducting thermal design. Finally, it summarises the key experiences and lessons learned from the project, as well as the limitations to consider when applying these methods to other projects.

2 THERMAL CONDUCTIVITY TEST

2.1 *Overview λ-test methodologies*

The thermal conductivity of soils in a laboratory can be determined using two approaches: the steady-state application of Fourier's law in various configurations or a transient method.

Steady-state test methods, however, have limitations. Water displacement within the pore space under sustained, relatively high thermal gradients over several hours as well as inadequate insulation can result in inaccuracies, as highlighted by Low et al. (2017) and Schedel et al. (2019).

Implementing a transient method, such as the needle probe technique, circumvents these issues while offering a more cost-effective and scalable solution for measuring soil thermal conductivity (Meier et al. 2024). For these reasons, the needle probe method was adopted for the SuedLink project.

2.2 *Summary of Methodology*

The test setup and the methodology for testing thermal conductivity of soils using the thermal needle probe as was done in the SuedLink project is described in detail in Meier et al. (2024) based on investigations of Drefke et al (2017).

The configuration of the needle probe and subsequent measurement to determine the thermal conductivity of a soil is already described in ASTM D5334 (2022) and IEEE Std 442 (2017). The process surrounding these steps were further specified within the framework of SuedLink as described by Meier et al. (2024) and include details on the test set-up, sample extraction, sample preparation as well as the various steps to be followed during the actual thermal conductivity measurement.

The unique aspects of the test methodology applied in the SuedLink is that the soil sample is (nearly) saturated before measurement starts and the thermal conductivity is measured continuously of a period of eight days as the sample dries out. Thereby the thermal conductivity-water content relationship of a soil sample is determined. A final thermal conductivity measurement is made after the sample has been oven-dried at a moderate temperature to avoid expelling crystalline-bound water, as this best reflects the in-situ conditions. An example of a test result for a sand is displayed in Figure 1.

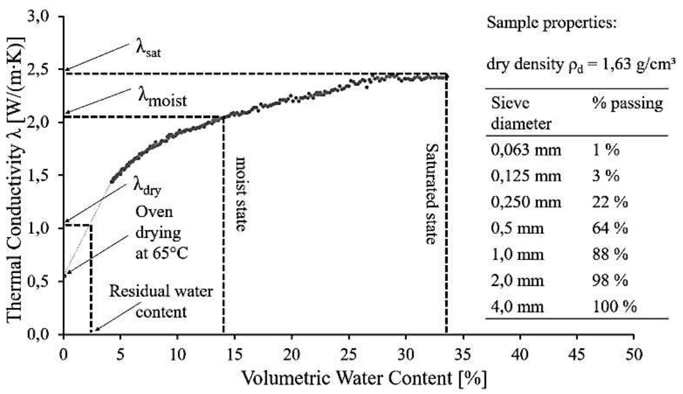

Figure 1. Example of a thermal conductivity test result for a sand

3 EVALUATING TEST RESULT

3.1 *Two zone thermal model for soil drying*

The thermal design of underground cables is based on the assumption that the heat from a cable above Groundwater level is sufficient to cause a redistribution of soil moisture content into two distinct zones (Cigré 1992a).

The inner "dry" zone, that is closest to the cable, undergoes a reduction of its moisture content and is characterised by a low thermal conductivity. The outer "moist" zone is not as strongly affected by the cable induced drying and therefore has a much higher moisture content and thermal conductivity than the dry zone. The assumption is also, that the moisture from the outer "moist" zone does not penetrate the inner "dry" zone to any notable extent (Cigré 1992a). The boundary between the dry and moist zone is defined by a specific isotherm representing a critical temperature rise compared to ambient conditions. As per standard industry practise, the 15 K Isotherm was often used to define the boundary between the dry and moist zone. The two-zone model is schematically displayed in Figure 2.

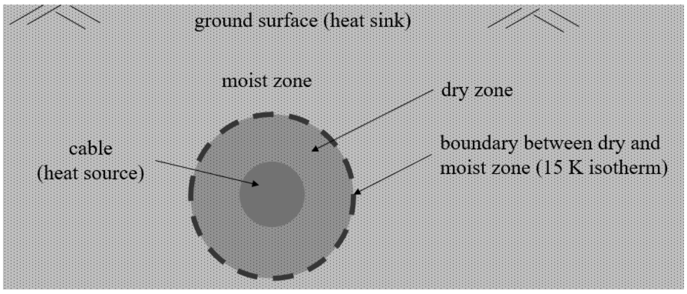

Figure 2. Two zone model adapted from Cigré (1992a)

3.2 *Characteristic Thermal Conductivities*

The thermal conductivity test result, as displayed in Figure 1 provides the relationship between the thermal conductivity of a specific soil sample and the water content. However, for the application of the two-zone model as described in section 3.1 two characteristic thermal conductivities that correspond to the dry zone (λdry) and the moist zone (λmoist) is required. Within the framework of the SuedLink project a methodology was developed in order to derive these two characteristic thermal conductivities and summarised below.

3.2.1 *Below Ground Water*

For the case where the cable is below ground water level the ground will always be saturated which is why the dry and moist thermal conductivities are the same and correspond to the thermal conductivity measured at the (near) saturated water content (see Figure 1 and Figure 4):

$$\lambda_{\mathrm{dry}} = \lambda_{\mathrm{moist}} = \lambda_{\mathrm{sat}} \quad (1)$$

3.2.2 *Above Ground Water*

For the case above ground water the water content in the moist zone corresponds to the water content of a soil in its driest natural state, i.e. when it is not influenced by external sources such as the heating from a cable.

Durner et al. (2021) created various one-dimensional water balance models for various climatic regions in Germany and modelled the driest natural state of a soil based on the following parameters:

- Weather data of different climatic regions
- Land use (maize agriculture, pasture, forest)
- Depth below ground surface
- Groundwater level
- Soil type
- Gravel content

Based on previous experimental studies on the partially saturated hydraulic properties of soils the model by Durner et al. (2021) defined five soil categories ("pure" sand, sand, loam, silt and clay) according to their silt and clay contents as displayed in Figure 3.

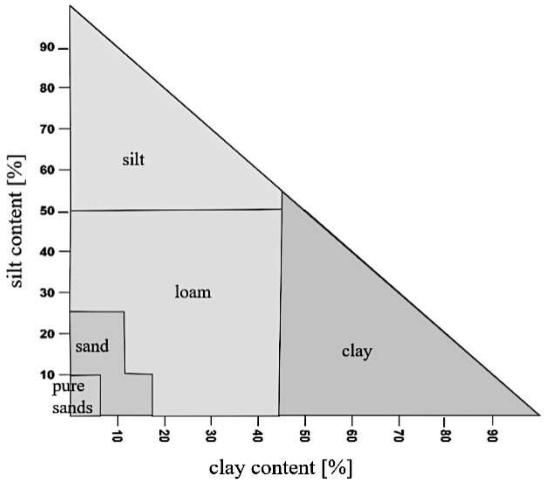

Figure 3. Soil categories as defined by Durner et al. (2021)

The results of the water balance model by Durner et al. (2021) were adopted for the purposes of determining the water content in the moist zone for the SuedLink project. The geotechnical engineers in the SuedLink project defined the lowest ground water level (LGW). This meant that once the above mentioned six parameters for a specific soil were known the minimum water content in the moist zone (wc_{moist}) could be estimated based on the study by Durner et al. (2021). In the example presented in Figure 1 the wc_{moist} = 14 Vol.-% and in the example presented in Figure 4 the wc_{moist} = 26 Vol.-%

Various numerical and experimental studies were commissioned within the framework of the SuedLink project in order to determine the water content in the dry zone (wc_{dry}).

The wc_{dry} varies significantly depending on whether a soil is granular (pure sand, sands) or cohesive (loam, silt, clay) as defined by Durner et al. (2021), see Figure 3.

Due to the open structure of granular soils and their comparatively high permeability, an initial conservative assumption was made that cable-induced drying could reduce the water content to the oven-dried state of the soil. However, based on a sensitivity analysis using a physical model that accounts for combined heat and mass transport (water and vapor), as well as experimental results from heated column tests indicate that granular soils do not dry out completely. This is why the project decided to set the threshold values of residual water content at 0.5 Vol.-% for pure sands and 2.5 Vol.-% for sands due to the higher fine-grained content when compared to pure sands. This slight increase in water content has a significant impact on the λ_{dry} for granular soils as the thermal conductivity increases rapidly with the water content (see example in Figure 1).

Due to the comparatively low amount of connected air-filled pores that allow water vapour transport as well as sufficient hydraulic conductivity to compensate for the outflow of vapourised water, cohesive soils do not dry out as much as granular soils when exposed to a heat source such as an HVDC cable. Based on results of numerical modelling performed as part of the project it was assumed that cohesive soils have a residual water content (wc_{res}) of 50 % of the water content in the moist zone after being subjected to the heating effect of an HVDC cable. This was a relatively conservative estimate which is why in certain cases a residual water content of 75 % of the water content in the moist zone could be justified.

Once the wc_{moist} and wc_{dry} of a soil was determined the λ_{moist} and λ_{dry} of a soil could be derived from the λ test result, as seen in the example Figure 1 for a granular soil (sand) and Figure 4 for a cohesive soil (clay).

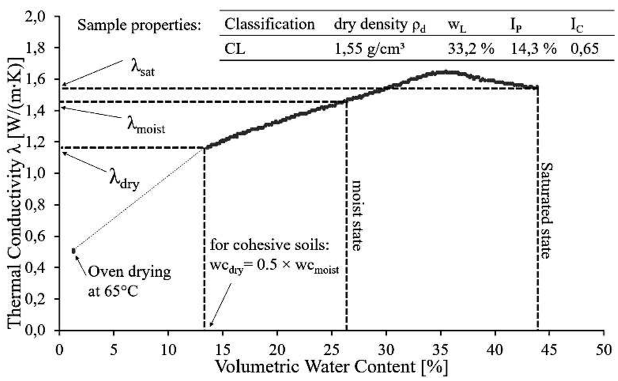

Figure 4. Example of a thermal conductivity test result for a clay

The various water contents that need to be determined for different soil types in order to derive the dry and moist thermal conductivities as described above are summarised below in Table 1.

Table 1. Summary of water contents to derive thermal conductivities above groundwater

λ_{moist}	λ_{dry}	
granular & cohesive soils	granular soils	cohesive soils
wc_{moist} = driest natural state as per Durner et al. (2021)	wc_{dry} = 0.5 Vol-% (pure sands) or 2.5 Vol.-% (sands)	$wc_{dry} = 0.5 \times wc_{moist}$

4 THERMAL GROUND MODEL

In the SuedLink project, the thermal ground model has proven to be an indispensable tool for understanding the factors influencing thermal design and identifying critical thermal sections along the HVDC cable route. The thermal ground model is typically derived from the geological profile, where the results of thermal conductivity tests are interpreted, and various soil samples are assigned to specific thermal soil classes. Within the thermal ground model, the geotechnical engineer evaluates the soil samples and test results to define distinct thermal zones, as illustrated in the example in Figure 5. When the same soil layer spans both above and below the groundwater table, it is separated into different thermal zones (e.g., zone 2 vs. zone 3 in Figure 5) because the soil's thermal properties vary significantly between its saturated, moist and dry states, as discussed in Section 3.2.

In general, the deeper an HVDC cable is installed, the greater the required spacing between cables to meet thermal design requirements, as the increased distance between the heat sink (ground surface) and the heat emitter (cable) reduces heat dissipation efficiency. In the example shown in Figure 5, the deepest point of the HVDC cable occurs along section B-B.

However, in reality, complex stratification and soil conditions often mean that depth alone does not determine the critical case. For instance, in section A-A of Figure 5, where a cable transitions from above to below the groundwater table, the upper soil layers above the groundwater—subject to more pronounced drying and consequently lower thermal conductivity—may govern the thermal design. Similarly, in section C-C, if the HVDC cable crosses other heat-emitting infrastructure, such as medium-voltage AC cables, this zone could also dictate the thermal design.

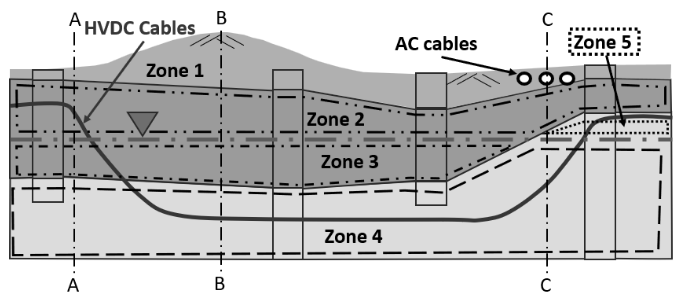

Figure 5. Example of a thermal ground model

5 THERMAL DESIGN

5.1 *Trenchless construction*

The thermal design of the cables varied significantly depending on the construction technique employed. Most trenchless crossings were designed for installation by means of HDD, where the drilling tolerances specified by DCA (2015) were incorporated into the thermal designs.

For trenchless construction techniques, the primary design parameter is the spacing between cables. This minimum spacing is determined through finite element modelling of the various sections, based on a thermal ground model. By applying the two-zone model, the moist and dry zones, as well as the cable spacing, are iteratively determined.

For the SuedLink project, a comprehensive set of calculations was carried out, covering the major part of the encountered scenarios. The results were summarised into a set of tables and included in the design manual for use by design engineers. The remaining cases, which were not addressed by the standard tables, required individual calculations. The design manual also provided guidance on how to adapt calculations from homogenous to layered soil conditions.

5.2 *Open excavation*

Where HVDC cables were installed using open excavations, the cover typically ranged between approximately 1.3 m and 3 m. For this construction technique, the cable spacing was kept constant at around 2 m, while the type of fill material, known as "bedding material," varied in thermal conductivity and thickness as determined by the thermal design which is primarily governed by the thermal conductivity of the surrounding in-situ soils.

The bedding material was installed with a minimum thickness of 20 cm below, above, and laterally to the HVDC cables, as illustrated in Figure 6. High cover and/or low soil thermal conductivity pose special requirements to ensure sufficient heat dissipation. In these cases, higher grade bedding materials or even greater thicknesses are required. Above the designated bedding zone, in-situ soil was used for backfilling.

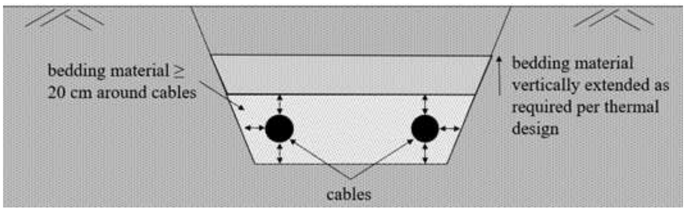

Figure 6. Sketch of open excavation with bedding materials

Bedding materials generally consisted of soil mixtures, such as sand blended with fine-grained soils (silt or clay), to achieve the required thermal conductivity. Where the in-situ soils met the specified requirements, they could also be utilised as bedding material. The SuedLink project employed various classes of bedding material, as outlined in Table 2, which, with the exception of the bedding classes B35 and B4, proved practical and scalable for large-scale application.

Table 2. Bedding material classes used in SuedLink

Bedding material class	λ_{moist} [W/(m.K)]	λ_{dry} [W/(m.K)]
B0	1.00	0.40
B1	In-situ soil	In-situ soil
B2	1.25	0.63
B3	1.67	0.91
B35	1,43	1,43
B4	2.50	2.50

To achieve the thermal conductivity required for a B35 and B4 class, a significant number of additives, such as graphite and cementitious binders, is necessary. However, the high additive content rendered B35 and B4 class materials unfeasible which is why their use was limited to exceptional circumstances.

6 EXPERIENCES AND LESSONS LEARNED

SuedLink is the first underground HVDC cable project to be constructed on such a scale, making it a pioneering initiative and a frontrunner for future underground cable projects. Similarly, the approach adopted in SuedLink for testing soil thermal conductivity, followed by evaluation and thermal design, has never been implemented on such a large scale. The invaluable experiences gained during the project have streamlined these processes.

The thermal conductivity test, as outlined in Section 2, demonstrated its ability to yield reproducible and accurate results. Furthermore, its semi-automated nature made the methodology scalable, enabling its successful application to more than 6,000 samples. This extensive database of test results will also support better predictions of soil thermal conductivity in the future.

To streamline the evaluation of thermal conductivity test results, a software solution (the thermal conductivity plug-in by GeoDin) was developed and applied during the project. This tool allowed designers to efficiently interpret the large volume of test data.

Due to the novelty of the approach of thermally classifying the subsoil, and in particular the development of the thermal models, the actual and correct implementation by the geotechnical engineers was particularly challenging at the beginning of the project. Towards the end of the detailed design phase, however, it was possible to record sufficient to good implementation of the approach in all sub-projects.

If the thermal designs, particularly the use of conservative thermal conductivity values for soils, had followed the standard approach applied to medium-voltage cables, the SuedLink project would not have been viable. The methodology developed within this project enabled significant cost savings by optimising both the required bedding material, reuse of excavated soil as bedding material and land use (cable spacing).

The additional geotechnical investigation efforts for thermal conductivity measurements were minimal compared to the monetary and environmental costs that would have resulted from over-designing the underground cables. Thus, the processes presented here have enabled a significantly more efficient thermal design.

7 LIMITATIONS

The water balance model developed by Durner et al. (2021) serves as the basis for determining λ_{moist}. However, since this model was specifically designed for the climatic conditions typical of Germany, its application to other geographical regions requires a thorough review of the model's parameters.

If a 90°C cable operating temperature is applied in other projects (compared to the 70°C used in SuedLink), the effect of cable-induced drying on cohesive soils should be reviewed, as less favourable initial soil moisture levels could lead to increased drying.

In the thermal design of the underground cables for the SuedLink project, neither global safety factors nor the principles of limit state design were applied. While various parameters inherently contribute to the thermal safety of the cables, these factors have not been quantified. Consequently, applying safety factors or partial safety coefficients during the thermal design would lead to an overly conservative and inefficient design.

The most significant parameters that increase the inherent thermal safety of an underground HVDC cable, especially in the case of SuedLink, are summarised below in Table 3. Considering these aspects, amongst others, the exclusion of safety factors in the thermal design could be justified.

Table 3. Significant parameters affecting intrinsic thermal safety of HVDC cables

Parameter	Explanation
Loading	The design is based on a chain of stationary worst-case assumptions: 100% load with simultaneously highest soil temperatures and lowest water content of the soil. In reality, all of this will only occur temporarily and often not simultaneously,
Steady state	In the thermal design only steady state conditions are considered. This means, that beneficial effects from seasonal temperature variations, infiltration from precipitation and fluctuations in groundwater levels amongst other aspects are not considered.
15 K Isotherm	It is assumed that the 15K isotherm represents the critical temperature rise that defines the boundary between the dry and moist zone. It has been proven, that this is applicable for granular soils, however, for cohesive soils the isotherm for the critical temperature rise lies approximately between 50 – 65K.

8 CONCLUSIONS

The thermal conductivity testing methodology developed as part of the SuedLink project was successfully applied to more than 6,000 soil samples. Its accuracy, reproducibility, and scalability have led to its adoption as an industry standard by the four German transmission system operators. At the time of writing, this industry standard is being revised into a national standard by the German Institute for Standardisation (DIN).

In addition to the testing, the evaluation process, including the thermal ground model, significantly improved the efficiency of the thermal design. This led to reductions in the required cable spacing and bedding materials, resulting in substantial cost savings and a lower environmental impact. These processes have set a precedent for future underground cable projects worldwide.

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