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THERMAL CONDUCTIVITY OF SILTY SOILS IN THE SOUTH-EAST REGION OF ROMANIA

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Abstract

The thermal properties of loess soil are essential for the distribution of heat generated by electrical cables in wind turbines. In these systems, where high-intensity electrical flow induces conductor heating through the Joule effect, the ability of the soil to facilitate heat transfer has a direct impact on the energy efficiency, operational safety and the durability of the electrical infrastructure, as inefficient thermal diffusion can lead to conductor overheating, affecting electrical resistance, degrading insulation and reducing cable lifespan. This study investigates the effects of density and moisture content on the thermal conductivity of silty soils at different compaction levels. Experimental tests were conducted on loessial soil samples compacted to 85-90% of the maximum dry density determined by the modified Proctor test. All measurements included the determination of dry-out curves to observe the variations of thermal conductivity with a gradual decrease in moisture content. The results indicate an increase in thermal conductivity with higher degree of compaction due to reduced porosity and improved particle contact.

Key words: *dry-out curve, loess, thermal conductivity.*

INTRODUCTION

Wind power is considered as one of the most efficient and sustainable forms of renewable electricity, contributing significantly to the reduction of greenhouse gas emissions and global dependence on fossil fuels. As global energy consumption continues to rise, the integration of renewable energy sources such as wind power is becoming a strategic necessity to long-term environmental and energy security challenges. Wind energy systems are clean, widely available and can be implemented on a large scale.

The rapid development of renewable energy technologies has led to a significant expansion of wind energy infrastructure across different terrains and climates. In this evolving energy landscape, the reliability and durability of underground electrical systems, particularly those associated with wind turbines are critical to maintaining overall system performance and longevity. These systems play a vital role in the safe and efficient transmission of electrical power from turbines to substations and the main power grid.

One of the technical challenges associated with underground power cable systems is the thermal management of conductors that carry high-intensity currents and generate heat through the Joule effect. This heat must be effectively dissipated into the surrounding ground to prevent overheating. The ability of the ground to transfer this thermal energy - determined primarily by its thermal conductivity - is a key factor in preventing excessive temperatures, minimising energy losses and extending the operational life of electrical components such as insulation materials and cable sheaths (Wang et al., 2024). Loess is thought to be derived mainly from glacial or periglacial material transported by wind after glaciers have retreated. However, loess can also be formed from other sources, resulting from the accumulation of eroded material in dry continental conditions, either cold or warm, which has subsequently been transported and deposited by the wind. Volcanic ash carried by the wind over long distances from its source can also be a significant contributor.

In many areas, loess is eroded by precipitation and runoff and then redeposited in accumulations similar to the original, but losing

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its aeolian character through sedimentation (Dragomir, 2002).

Loess a wind-deposited, fine-grained soil is common in many regions with large-scale wind energy projects. It forms extensive sedimentary layers that often underlie wind turbine foundations and cable routes. Its physical properties, such as porosity, moisture retention capacity, and mineral composition, vary significantly with compaction and environmental conditions, affecting its thermal behaviour. The inherent variability in the structure and composition of loess presents a challenge to the design of consistent and safe cable installations. Inadequate thermal conductivity in such soils can lead to conductor overheating, insulation degradation and a reduction in the reliability of the underground cable system (Sangprasat et al., 2024). For this reason, a thorough investigation of the thermal conductivity of loess is essential.

In this study, soil samples were collected from a construction site near Medgidia, Constanța County, at a depth between 1 to 2 meters. The site was selected based of its typical loessial profile, which is common in south-eastern Romania and representative of the conditions encountered in wind farm development. The testing was conducted at the Geotechnical Laboratory of the Technical University of Civil Engineering Bucharest. The soil was identified as loessial, characterised by fine texture, high capillarity and moderate to high water retention, making it suitable for detailed thermal analysis.

The aim of this work is to provide insight into the optimisation of underground electrical design in wind energy applications by highlighting the influence of soil properties, in particular moisture content and maximum dry density on thermal conductivity. This approach is in line with the wider aims of improving renewable energy infrastructure through innovations in materials science and geotechnical engineering.

MATERIALS AND METHODS

Methods for thermal conductivity measurements

The most relevant thermal parameter of the earth is the thermal conductivity λ, as it directly influences the heat transfer processes in underground applications. For the preliminary design of complex energy foundations, the detailed sizing of standard geothermal systems and the engineering layout of underground electrical cables in wind energy infrastructure, thermal conductivity can be reasonably estimated using empirical diagrams that correlate with water content, saturation density and soil texture. This approach provides a practical and sufficiently accurate basis for early-stage thermal analysis in geotechnical and energy systems applications (Brandl, 2006).

In the laboratory, the experimental procedure was carefully designed to avoid any disturbance of the internal structure of the loess soil samples or alterations to the local thermal environment. Ensuring minimal disturbance is essential to preserve the native properties of the soil, which directly affect the accuracy of the thermal conductivity measurements. To achieve this, no pushing or mechanical insertion forces were applied to the thermal needle during installation (ASTM D5334-14 STM, 2014) (Figure 1).

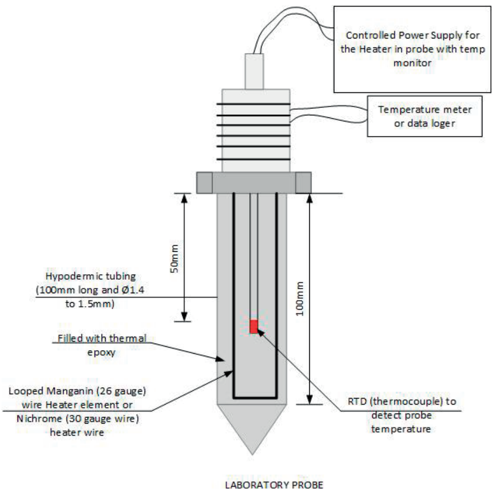

Figure 1. Thermal needle apparatus (IEEE Std 442™, 2017)

Instead, a precise pre-drilling method was used to create an access path within the sample, see Figure 2, allowing the thermal needle to be placed in direct contact with the soil along its entire length without causing deformation or compaction. This technique ensures uniform thermal contact between the probe and the surrounding material, which is essential to replicate in-situ conditions and avoid artificial thermal gradients. Pre-drilling also helped to eliminate potential sources of mechanical heat that could interfere with the temperature readings during the test.

Figure 2. Pre-drilled soil sample

To further minimise errors, special attention was given to thermal stabilisation prior to measurement. The sample and instrumentation were allowed sufficient time to reach thermal equilibrium with the laboratory environment. This stabilisation period ranged from a few minutes to over an hour, depending on initial temperature differences and environmental factors such as air flow or sample moisture content levels. The thermal conductivity measurement cycles were not initiated until a stable temperature had been reached and maintained.

The entire test protocol strictly followed the methodology outlined in IEEE Std 442™, (2017) – "IEEE Guide for Thermal Resistivity Measurements of Soils and Backfill Materials". This standard prescribes installation procedures, measurement timing, calibration requirements and data interpretation techniques necessary to ensure reliable and repeatable results in assessing soil thermal resistivity. Adherence to this guide will ensure consistency in the evaluation of loess soil behaviour under thermal stress conditions typically encountered in energy infrastructure projects.

Methods for laboratory measurements

The thermal needle probe is primarily used to determine the effects of variations in density and moisture content on the thermal resistivity of the soil. This method is widely recognised in geotechnical and electrical engineering for its accuracy and adaptability to various soil types. It operates by applying a controlled and localised heat pulse and measuring the resulting temperature change over time, allowing the determination of soil thermal properties through analytical modelling.

The probe can be used to both undisturbed and reconstituted soil samples compacted using the Modified Proctor test. Undisturbed samples preserve the natural structure and stratification of the soil, while reconstituted soil samples allow controlled variations in compaction and moisture for comparative studies. The ASTM D1557-12 (2021) standard was used to determine the maximum dry density and optimum moisture content required for soil compaction. This standard is particularly relevant for the evaluation of soils used in civil engineering applications, such as backfill around buried utilities.

For this study, test samples were compacted to 85% and 90% of the Modified Proctor maximum dry density. These values represent realistic field conditions encountered after backfilling and compaction of soil in cable trenches. Compaction was carried out in five uniform layers using mechanical energy equivalent to 2700 kNm/m³, ensuring homogeneous sample preparation and consistent test conditions. The layered approach helps to minimise void heterogeneity and improve the reproducibility of thermal measurements.

After compaction, the soil samples were allowed to equilibrate with the laboratory temperature for a period to eliminate transient thermal effects. This step is essential to ensure that the initial thermal state of the sample does not bias the results, particularly given the sensitivity of thermal resistance to moisture migration and temperature gradients.

In practical field applications, particularly in wind energy infrastructure, foundation soils are compacted after cable installation to achieve densities ranging between 85% and 90% of the Modified Proctor maximum along the entire underground cable route. Ensuring consistent soil compaction is not only vital for mechanical stability but also has a significant impact on the thermal performance of the buried cables. Poorly compacted soil can retain air voids which act as thermal insulators, reducing the ability of soil to dissipate heat effectively and creating a risk of conductor overheating. Therefore, replicating these field conditions in the laboratory provides an accurate representation of operational scenarios and helps in the design of optimised cable burial systems.

Analysis of thermal conductivity test results

The analytical model for calculating thermal resistance has been developed based on the assumption of an infinite linear heat source dissipating heat in an infinite homogeneous medium. Under these idealised conditions, the thermal resistivity (ρ) (IEEE Std 442™, 2017) can be calculated using the following equation:

$$\rho = \frac{4\pi(T_2 - T_1)}{q \ln\left(\frac{t_2}{t_1}\right)} \quad (1)$$

where:

r is thermal resistivity (K·m/W);

T_1 - temperature measured at some arbitrary elapsed time (K);

T_2 - temperature measured at another arbitrary elapsed time (K);

q - dissipated per unit length (W/m);

t_1 - elapsed time at which temperature T1 is recorded (min);

t_2 - elapsed time at which temperature T2 is recorded (min).

Initial thermal transients occur due to the finite diameter of the thermal probe and are not representative of the ideal line source model. Similarly, boundary effects can occur due to the finite size of the soil sample container, leading to distortions in the measured thermal profile at later times. To ensure accurate calculations, the measured data must be carefully filtered to exclude these non-linear periods.

A standard approach is to plot the recorded temperature against the logarithm of time. The linear portion of this semi-log plot is identified as the valid interval for analysis. Data points within this region reflect stable thermal diffusion unaffected by the probe transients or edge boundary conditions.

Deviations at the beginning or end of the curve indicate either insufficient thermal stabilisation or the onset of confounding factors such as heat reflection from sample boundaries or moisture redistribution.

To simplify the calculation process and increase reliability an alternative form of the equation is often used. If the temperature change (ΔT) is measured over a complete logarithmic cycle, the resistivity can be approximated as (IEEE Std 442™, 2017):

$$\rho = \frac{4\pi}{2.303q}\Delta T \quad (2)$$

This formulation allows a simpler interpretation of the linear segment and is endorsed by the IEEE Std 442™ (2017) for thermal resistivity assessments. The use of these analytical techniques provides a robust framework for comparing thermal behaviour under varying moisture and compaction conditions. Three determinations were made for each sample (Figure 3).

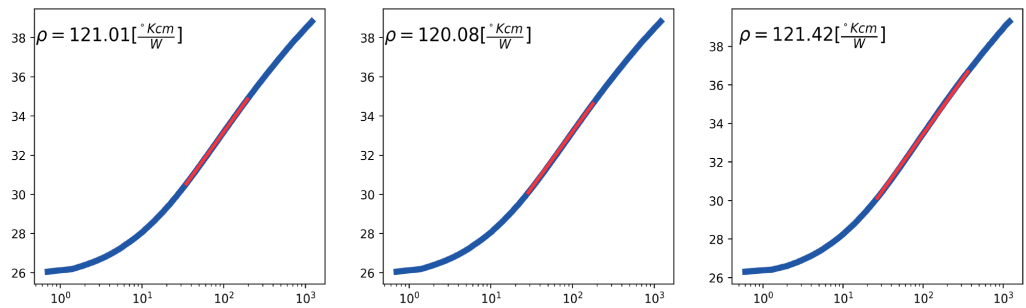

Figure 3. Thermal Resistivity Curves

Analysis of the geotechnical parameters of the soil

In order to characterise the investigated soil, a comprehensive programme of geotechnical laboratory tests was conducted to determine the physico-mechanical properties of the material. These tests were designed to provide essential data to evaluate the behaviour of the soil under different conditions, particularly for applications involving thermal performance, degree of compaction and load-bearing capacity. An understanding of these parameters is essential for the integration of thermal conductivity knowledge into practical design. Granulometric (particle-size) analysis indicated that the soil samples tested fell within the classification range of silty clay to clayey silt, as shown in Figure 4.

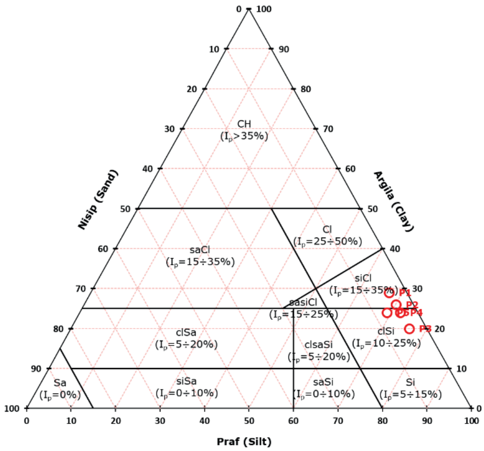

Figure 4. Ternary diagram of the soils

This classification suggests a fine-grained soil composition, which is typically associated with moderate permeability and relatively high-water retention capacity. Such properties have a direct influence on the thermal conductivity of the soil, as finer particles and higher moisture content levels can either promote or inhibit heat flow depending on their spatial arrangement and degree of saturation ration.

The Atterberg limits were determined to evaluate the soil's plasticity characteristics. The measured liquid and plastic limits indicate a medium plasticity index, indicating that the soil has a moderate deformation potential under variable moisture conditions (Figure 5). This plasticity range is important in determining how the soil content to seasonal changes in moisture, affecting both its thermal and mechanical stability. Soils with medium to high plasticity tend to be workable in the field, but their sensitivity to moisture variations requires careful consideration in the design of earthworks.

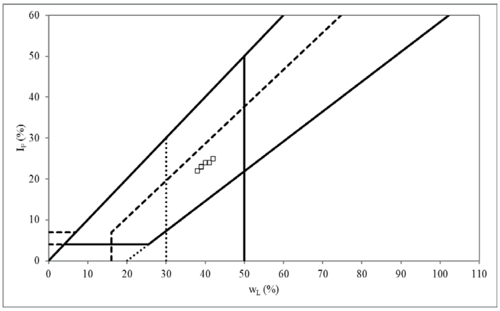

Figure 5. Soil plasticity

To further assess the quality and potential performance of the soil, the organic matter content was also determined. Laboratory results indicate that the organic content is between 2% and 3%. Although this level is not excessively high, it may still influence the soil's compaction behaviour, strength, and long-term stability. Organic materials tend to reduce dry density and increase water retention, which can alter thermal conductivity and pose risks in load-bearing applications, especially when the soil is used as backfill material.

To determine the optimum compaction parameters, Modified Proctor tests were performed on all tested samples in accordance with ASTM D1557. The test results helped identify the optimum moisture content and the corresponding maximum dry density necessary for achieving maximum density under in-situ conditions. The Modified Proctor curve (Figure 6) shows a clear peak, indicating the optimum moisture content at which soil particles are in the denseness state, minimising air voids and maximising thermal conduction potential.

In addition, California Bearing Ratio (CBR) tests were carried out in accordance with ASTM D1883 (2021) to assess the strength and bearing capacity of the soil. The CBR test results (Figure 7) provide critical information for assessing the mechanical performance of the soil, particularly the suitability of the subgrade material.

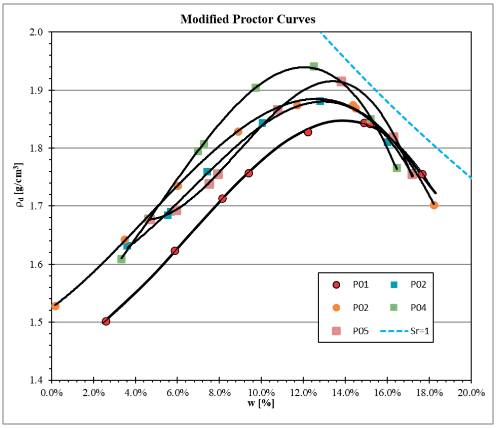

Figure 6. Modified Proctor Curves

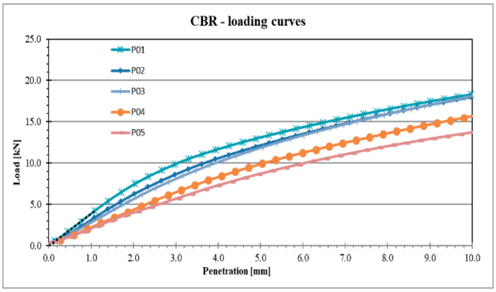

Figure 7. CBR Curves

Table 1 shows the compiled optimum compaction parameters, including the optimum water content (w_{opt}), the maximum dry density ($\gamma_{d,max}$) and CBR values for each of the conditions tested.

Table 1. Optimal compaction parameters

w_{opt}	$\gamma_{d,max}$	CBR	
		1	2
[%]	[g/cm^3]	[%]	
13.9	1.85	66.53	65.59
13.0	1.88	57.24	60.96
12.6	1.88	52.94	59.41
12.0	1.94	41.48	49.5
13.4	1.92	36.62	43.62

RESULTS AND DISCUSSIONS

The testing programme involved preparing samples at different Modified Proctor compaction levels, specifically 85% and 90%, to replicate field conditions typically encountered during the backfilling process (Olinic & Olinic, 2016) at underground cable installations. Each soil sample was meticulously prepared under controlled laboratory conditions to ensure repeatability and reliability of results. Compaction was carried out in successive layers to maintain a uniform density distribution throughout the soil sample volume.

All samples were pre-drilled along the vertical axis to accommodate the thermal needle probe, ensuring optimum thermal contact and minimising disturbance to the compacted matrix. This pre-drilling procedure is critical for accurate thermal conductivity measurements as it prevents deformation around the probe and eliminates artificial voids that could distort temperature readings.

Three independent resistivity tests were carried out on each sample at different moisture contents, allowing conductivity trends to be observed as a function of moisture content. The range of moisture contents tested ranged from near optimum compaction values to air-dried conditions. This enabled a detailed drying curve to be constructed, characterising how thermal resistivity evolves with progressive moisture loss.

Three independent resistivity tests were carried out on each sample at different moisture contents, allowing conductivity trends to be observed as a function of moisture content. The range of moisture contents tested ranged from near optimum compaction values to air-dried conditions. This enabled a detailed drying curve to be constructed, characterising how thermal resistivity evolves with progressive moisture loss

Figure 8 shows the variation in thermal conductivity over the range of moisture contents for both 85% and 90% compacted samples.

A comparative analysis of the curves highlights the significant effect of the degree of compaction level on thermal performance.

This observed behaviour confirms the critical role of both moisture content and dry density in optimising heat dissipation around underground conductors. The results reinforce the importance of proper site preparation and moisture control to ensure efficient thermal management in wind energy infrastructure.

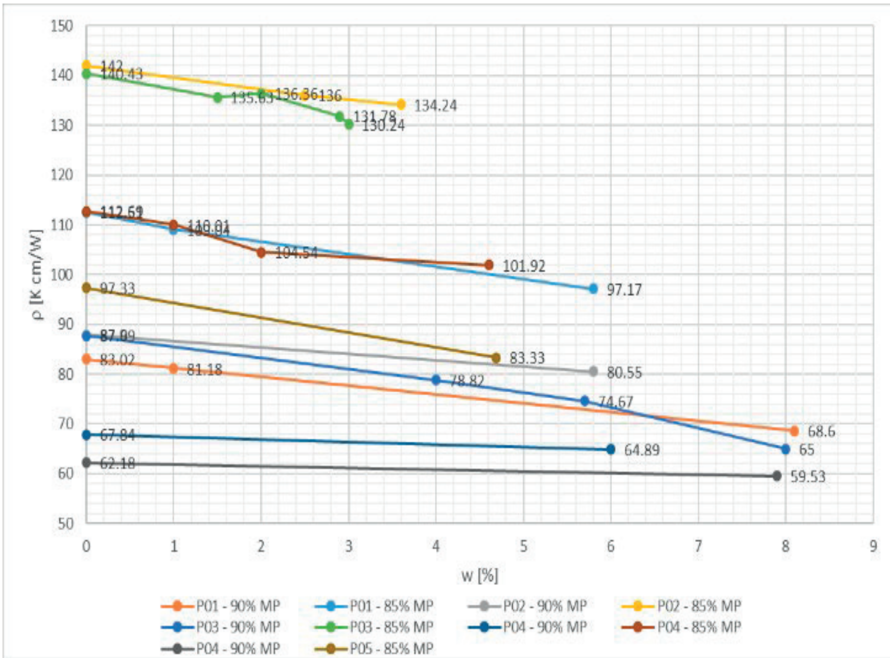

Figure 8. Thermal conductivity of tested soil

CONCLUSIONS

The experimental results clearly demonstrate that moisture content is a primary factor controlling the thermal conductivity of loess soils. The relationship between water content and heat transfer efficiency is non-linear and subject to threshold behaviour, influenced by soil microstructure and particle interactions (Nikiforova et al., 2013).

Three main regimes were identified:

- Dry state (low moisture content): In the absence of sufficient moisture, loess has very low thermal conductivity. This is mainly due to the dominance of air-filled pores which act as thermal insulators and significantly reduce the rate of heat transfer through the soil matrix.
- Moderate saturation (10–20%): As water content increases, capillary bridges begin to form between particles, allowing more efficient heat transfer. This is the optimum range for thermal conductivity where the combined effects of the higher thermal conductivity of water and increased interparticle contact significantly reduce the resistivity.
- High saturation (>40%): Surprisingly, thermal conductivity does not continue to increase indefinitely with moisture content. At high saturation levels, water tends to occupy voids in a discrete manner, forming capillary barriers. These restrict heat flow and can reduce conductivity by disrupting of continuous solid-liquid pathways.

The generation of drying curves proved to be an essential tool for understanding how progressive moisture loss affects thermal performance. These curves provide a dynamic perspective on how loess soils behave under real environmental conditions, particularly after compaction which is typical of wind farm installations.

In particular, below 8% moisture content, the thermal conductivity of remoulded loess samples prepared using the modified Proctor test showed inconsistent or subdued responses. Only when a stable temperature was achieved and maintained, the thermal conductivity measurement cycles were initiated. This variation is likely to be related to irregularities in void ratio and uneven moisture distribution within the soil matrix at very low water contents. Additionally, the degree of compaction level plays an important role in determining thermal conductivity. At densities above 85–90% of the maximum dry density (according to Modified Proctor), the reduction in pore air volume significantly improves heat transfer through the soil. The denser particle arrangement creates more efficient conductive pathways, which is critical in preventing overheating of buried electrical systems (Mostafa et al., 2018).

In conclusion, the synergy between moisture content and dry density must be carefully considered in the thermal design of underground electrical installations. Loess soils, although generally suitable due to their fine structure and moisture retention properties, require site-specific assessment and control of compaction and drainage conditions to ensure reliable performance.

To improve thermal properties (Martinez et al. 2019), a mixture was proposed that exchanged heat more effectively than soil particle contact points, and a linear relationship was obtained between $CaCO_3$ content and thermal conductivity. The thermal conductivity increased by 50% when the $CaCO_3$ content exceeded 8%.

Further research is recommended to investigate long-term thermal behaviour under cyclic moisture conditions and to quantify the influence of soil anisotropy and mineralogical variability on thermal conductivity.

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