A MODEL FOR THE EVALUATION OF HEAT LOSS FROM UNDERGROUND CABLES IN NON-UNIFORM SOIL TO OPTIMIZE THE SYSTEM DESIGN

by

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With the proliferation of technologies and underground systems, analysis of thermal fields in soil has become a topic of great interest in the developing technology of buried structures. In this work, we have investigated the steady-state temperature field (from linear heat sources – buried cable) in a different type of soil and excavation geometry. In a laboratory, a physical model was built on scale, which reproduces an "undisturbed" area containing a linear thermal source. This scale model was produced for experimental activity. A measuring chain was made to analyze the thermal field in various types of soils, by varying the electrical current through the line source. The physical model was recreated using a finite volume calculation software. Analysis of the different field system configurations were completed and we have studied a model for the improvement of the design method.

Key words: *dry soil, buried cable, FEM model, electrical current, linear thermal source, design method, excavation geometry*

Introduction

This work derives from the need to study thermal fields generated in a soil that is increasingly used to contain various types of technological systems (high-voltage electrical cables, pipes for the exploitation of geothermal energy and others). A particular concern is given to the underground power lines whose installation is going through an important growth in order to mitigate the environmental impact of electricity distribution. Hence it is essential to understand the thermal behavior of the soil. Resistivity is fundamental for the sizing of cables [1, 2]. The thermal energy generated by the cables needs (Joules) to be dissipated through the surrounding soil [3-5]. Dissipation must be such as to maintain the safe operating temperature of cables that is compatible with the composite materials. Therefore it seems obvious that correctly assessing the thermal behavior of the soil is very important to determine the diameter of cables and other characteristics. In this regard it should be noted that this problem has not received an adequate attention. In the IEC 287-2-1, the sizing of the underground electrical cables depends on the presumed average thermal conductivity values. The IEC standard covers a range of average resistivity variation that is specific to certain soils, between 0.7 °Cm/W (very wet

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soil) and 3.0 °Cm/W (very dry soil) [6-8]. The reference values given by the standard to describe the thermal resistivity of the soil are based on the theory defined by de Vries [9]. Such theory has been considered to be correct for many years. The criterion is based on the fact that overall thermal resistivity is a combination weighted on the resistivity of the various elements characterizing the soil.

However, the thermal resistance of the soil depends on many other factors, such as: the particle size characteristics, the lack of homogeneity and the water content [10]. Very dry soils are usually characterized by high thermal resistance due to interstitial air gaps. When the amount of water in the soil increases, the thermal resistance of the soil decreases because the water is a good conductor. A soil saturated with water has a lower thermal resistance than a dry one. However the more rapidly the water content increases, the more the thermal resistance of a dry soil decreases. The process of decrease becomes slower near saturation [11-13].

A particular attention has been given to heat transfer of the underground cables set in dry soils. It has not been taken into consideration the presence of humidity in the soil. These types of soil can determine a certain kind of condition such as thermal stress experienced by electric cables and this can provoke a decrease regarding its lifetime.

In order to study the thermal field in these circumstances we first set up a scale experimental model simulating the thermal behavior patterns of different types of dried soil [14, 15] used for the installation of power lines [16]. We then constructed a computational model using certified FEM software, in order to help the study and analysis of the phenomena of heat transfer under the various soils where cables are normally installed. In fact, it has been experimentally demonstrated that the IEC 287 reference standard calculation method underestimates the average thermal resistance of dry soil leading to an installation of cables that are too small. Such undervaluation has been already highlighted in some studies [17, 18].

The first step of the work was making computational model with a FEM software. The second step was the validation of the FEM model by comparing the data obtained and using an experimental model made in a laboratory. Then the computational model was used as a tool to study different system configurations. Different geometry was used to simulate the excavation (with a linear thermal source) in order to understand how these parameters affect heat dissipation in the surrounding soil. Lastly, the model allowed a critical analysis of the standards providing the thermal resistance values around cable installations and led to the determination of a correlation between the values of the standards and those determined by our study, in order to approximate as much as possible the working conditions of an underground cable.

The geometric relations characterizing the dimension of the excavation usually do not have a high level of investigation in the field of the current regulations, but they actually have great influence on how the heat around the electrical cable is discharged.

The ultimate goal of this study is to determine a connection in order to quantify a correction factor to the formula recommended by those regulations for the valuation of the underground thermal resistance due to a change of the geometric conditions characterizing the excavation setting. The specific case we are interested in deals with the electrical cables set underground.

Implementation of the FEM model

The mathematical model implemented for the study of the thermal field in situations similar to those of the physical model was developed through the use of numerical simulation software (FEM certified, developed by Ansys). The goal was to develop a calculation process with which to study the thermal effects behavior of the soil crossed by linear thermal sources.

This work has allowed us to demonstrate how the use of a FEM code provides basic design inputs with a reduced commitment in terms of costs and time.

The procedure we followed to carry out the simulation consisted of initially generating a wide grid mesh to quickly obtain a solution and test the accuracy of the hypotheses we had made. Subsequently, it was necessary to make the grid thicker to increase the resolution and accuracy of the solution. The thickening procedure was also necessary in the computational domain regions where there were strong gradients of field variables, in order to avoid a locally or globally unrealistic solution. We recreate a mesh to simulate a thermal field using the FEM software [19].

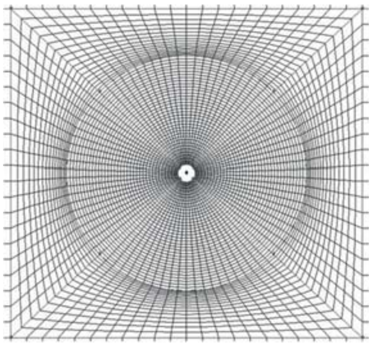

Figure 1. Detail of the final mesh showing the area around the tube in the installation excavation

Numerous simulations were carried out before finalizing the geometry configuration of the mesh, as shown in fig. 1, characterized by having a circular connection area after the cable with a diameter that was 3 times wider than the cable, with each side divided into 16 parts and with the size of the surrounding terrain being 3 times larger than the experimental apparatus. There were 30.074 nodes in this mesh.

We have tried to recreate a mesh in order to simulate a thermal field with a FEM software able to reproduce the experimental system of the laboratory. After we have taken into consideration the peculiar type of geometry it has been decided to study the problem through a 2-D plane geometry: a cross-section of the experimental system. This can be useful to accelerate the valuation and then work on the smallest number of geometric variables possible.

Several configurations of the mesh geometry have been tested in order to reach the one considered the closest to the experimental results obtained in the laboratory. The mesh described is a "quad map".

In the mesh the position of the underground cable is at the same level, in terms of depth, of the cable set in the experimental system. Around the circular geometry representing the cable it has been created a circular mesh (with a thick geometry because in this way it is possible a better comprehension of those phenomena connected to the area where the electric cable and the soil get in touch with each other) concerning the ground which is in a direct contact with the thermal source, characterized by a concentric cable, whose diameter is three times bigger than the diameter of the cable. This area represents a connection zone made of sectors of angle crowns surrounding the cable. The mesh has been tested with and without such connection zone.

The portion of the mesh representing the ground partially close to the underground cable (hence it is located between the annulus and the less disturbed ground) is made of equilateral trapezoids that once deformed will form a square. Many tests have been performed for the square mesh which has a portion of the ground that is most disturbed by the presence of the cable. The lengths of its sides vary with values which are 8, 16, and 32 times bigger than the diameter of the cable. The cable has 4 arcs. Each arc is of 90° and is divided into 8, 16, and 32 parts. The conjunction segment (that from now on it will be called "transversal") between the edge of the square surrounding the cable and the intersection zone between the diagonal of the square and the annulus representing the ground in direct contact with the cable is formed by 15 parts. The distance between one part and another has an increasing value.

The mesh representing the most distant portion of the ground, hence the one which is less disturbed by the operating laying excavation of the cable, is made of cells which tend to decrease towards the lateral edge of the mesh. For what concerns its extension some tests have been performed by starting with a 1:1 scale mesh respect to the one represented by the experimental system, until we reached a mesh thrice bigger than the one we started with.

Several mesh tests have been performed every time the geometric parameters, previously mentioned, varied. The equations solved by the software, having a convergence trend, were not supposed to create coarse approximations due to mathematical problems (propagation of error). Finally it has been calculated its accuracy for what concerns the experimental tests performed in the laboratory described in the following paragraphs.

Once these simulations were over we chose the geometry of the mesh with the best approximation to the experimental values. For the next steps of the study we decided to choose the one characterized by a circular connector, right next to the cable, with a diameter three times bigger than the one of the cable, with the connector square, circumscribing every part of it, whose side is 16 times bigger than the diameter of the cable, and every side of the square is divided into 16 parts; the dimension of the surrounding ground is thrice bigger than the one of the experimental system.

In a previous article [19] it has been demonstrated the accuracy of this mesh and its effectiveness in the approximation of the data obtained experimentally.

Table 1. Characteristics of the materials used in the simulations

Material	Density	Specific heat	Thermal conductivity
	δ [kgm^{-3}]	c_p [kJkg^{-1}K^{-1}]	λ [Wm^{-1}K^{-1}]
Sand	1700	837	0.35
Soil	380	900	0.08
Wood	600	2721	0.44
Concrete	1400	1000	0.93
Polystyrene	20	1300	0.04

The materials considered in the simulations had the following physical properties (tab. 1). The values had been previously taken from bibliographical references [20, 21]:

Simulations were then performed to compare the output data of the FEM software with the experimental data (tab. 2) in regard to 3 configurations: with the excavation filled with "sand only" (Case A), "sand + polystyrene" (Case B), and "sand + concrete" (Case C). Both the polystyrene and concrete filled a thickness of 5 cm between the backfill sand that surrounded the cable and ground level.

Table 2. Data extracted from the experimental tests

Case	Cable temperature	Average temperature environment	Voltage	Amperage	Specific heat capacity, Q	Thermal resistance
	[°C]	[°C]	[V]	[A]	[Wm^{-1}]	[KW^{-1}m^{-1}]
A	61.45	17.61	2.22	7.76	12.28	3.57
B	66.54	19.36	2.40	8.33	14.3	3.30
C	63.66	18.08	2.32	7.72	7.72	3.56

In tab. 2 the "Specific heat capacity" is the heat entered in the ground through the Joule effect. A certain amount of heat is introduced thanks to a power cable for every linear meter of the cable.

Description of the experimental model

The experimental apparatus was designed to simulate the operating conditions of an underground power line [22] in dry soils and allow the analysis of thermal-related sizing.

The model was made of a wooden container simulating, in terms of scale, the surface area of the soil that covers an electrically charged cable. All of this was installed in an area that was isolated from the outside environment and air conditioned.The container was a parallelepiped type container that was 1.9 m long, 1.5 m wide, and 0.35 m high. Its top part was open, while the other five sides were made of 0.02 m thick wooden panels (fig. 2). The internal walls of the container were covered by a waterproof enamel to prevent the transfer of moisture from the container to the surrounding environment. In order to avoid a direct contact with the flooring, a layer of polystyrene foam was laid to keep the container off the ground. The presence of a power line was simulated using a stainless steel tube with a diameter of 0.005 m, a thickness of 0.25 mm, and a length of 1.5 m. This cable was supplied with a precise voltage through a resistor system: a system standard and others in parallel. In this way we obtained the controlled heating of the tube in terms of Joules, simulating the operation of a real power line. Suitably sized and spaced holes were made on the long side of the container. Copper wires were inserted into the holes to act as supports for the fixing of thermocouples (fig. 2). In order to avoid a deformation of the container, springs were connected to one end when threading through the copper wires. It was therefore possible to stretch the wires without deforming the container, since the tension is absorbed by the springs. The thermocouples (a total of 25) were of "K" type, Chromel (Ni-Cr) (+)/Alumel (Ni-Al) (–), and they were installed in the container at three depths, inserted inside the case on the aforesaid metal wires, as can be seen in fig. 2.

The three levels of thermocouples allow a complete mapping of the soil that fills the casing, giving the possibility of reconstructing the thermal field around the heat sources. In the middle of the model (shown in fig. 2) there is a wooden compartment in which there were 5 other type "K" thermocouples; the compartment in the middle simulated the excavation area for the installation of the electrical cables and allowed an assessment of the effects of the thermal field in the backfill soil in the vicinity of the cable. This channel was located at 0.2 m from the bottom of the container, and had a width of 0.08 m, a depth of 0.15 m and a length equal to the width of the container of 1.5 m. The power supply system and data acquisition consisted of a generator, a computer, two resistors in parallel and a resistance standard. Two 1.75 ohm resistors (PowerOhm Resistor Inc., model S650) were connected to a generator. The resistance standard ($R_c = 0.1\ \Omega$ at 20 °C) allows the measurement of the voltage through the dropping of its value.

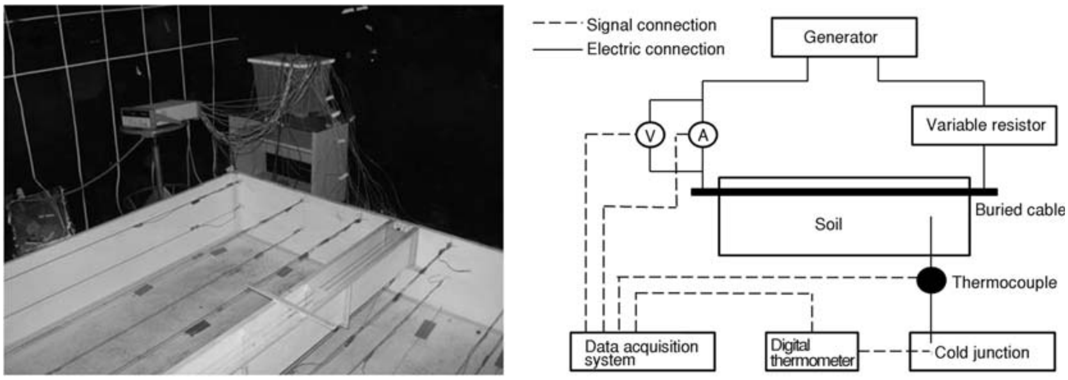

Figure 2. Experimental apparatus measurement chain. Experimental apparatus and scheme of principle

The data acquisition system was an HP AGILENT 34970A DATA model. The thermocouples were connected to the specific slots, which were inserted in the data acquisition device; the data acquisition device provided ΔT as its output between the cold coupling at a known soil temperature (fig. 2).

The data acquisition device was connected to a computer through a serial port. While allowing the commencement of the measurements using software, this took into account the sampling and storage of the temperature values of all the thermocouples scanned during the experiment as well. Once this was completed, the part of the container simulating the undisturbed soil was filled with a mixture of expanded clay with known thermophysical characteristics. The backfill material used to simulate the soil around the cable conduit was river sand. The thermal conductivity value of the sand was measured with specific instruments (Surveyor of the thermal conductivity of the ground: MAE A5000T + Thermal conductivity probe: MAE CTS-45).

Three different configurations of the excavation were carried out in order to simulate the installation of a cable. The first 0.03 m of the outer layer of the cable conduit, the layer in contact with the external environment, was alternatively composed of materials with different physical characteristics (sand: Case study A; polystyrene: Case study B; concrete: Case study C), but of equal thickness.

Table 3 shows the thermal conductivity values of the materials we used and the thickness of the materials in the three cases we analyzed through experimentation.

Table 3. Values of thermal conductivity and thicknesses of the materials used to cover the excavation

Material	Thermal conductivity λ [Wm^{-1}K^{-1}]	Thickness [m]		
		Case study		
		A	B	C
Concrete	0.93	0.0	0.0	0.03
Polystyrene	0.04	0.0	0.03	0.0
Sand	0.35	0.15	0.12	012

Comparison of data obtained from the FEM model with those measured in the experimental apparatus: experimental validation and critiques of the standards

We compared the output data provided by the software with the experimental values of heat transfer and the temperatures of a string of thermocouples in the vertical section of the excavation between the underground cable and the surface of the ground level. In addition, the variances and percentage errors were calculated. We used this data to calculate the value of the thermal resistance of the soil in 3 cases. Lastly, the trends of the isotherms inside the excavation are shown.

As shown from tabs. 4 and 5, the maximum error in relation to the heat was $\Delta = 4.06\%$, and $\Delta = 5.51\%$ in regard to the temperatures. These values are on an average which is generally acceptable. We observed that the FEM model responded to different types of materials used with varying conductivity, by demonstrating a high level of reliability and an error value which was almost constant (tab. 4).

Table 4. Amount of heat exchanged: comparison between the experimental and simulated values

Case	Q [Wm^{-1}]		Error %
	Simulated	Experimental	
A	12.75	12.28	3.83
B	14.87	14.3	3.99
C	12.28	12.8	4.06

For brevity we show (tab. 5) a small but significant part of the test results comparison that allowed us to validate the FEM model compared to the experimental apparatus.

The percentage errors, when we must approximate the temperature values and those estimated in an experimental way or calculated during the simulations, show the good quality and the accuracy of the improved FEM model. It should be pointed out that such model simulates the behavior of dry soils. The presence of humidity in the soil invalidates the capacity of the soil to disperse the heat, in this way we have a more successful dispersion of the heat produced by the Joule effect through the power cables. This is why dry soils tend to be the ones producing a higher thermal stress on the cables. Hence it is vital to have a deep knowledge of the conductivity characterizing dry soils.

Table 5. Temperature values of the thermocouples: comparison between the experimental and simulation data

	Position of cable		Temperature		Δ[K]	Δ %
	Depth [m]	Co-ordinate reference	Experimental [K]	Simulated [K]		
Case A	0	0.93	334.60	333.22	1.38	3.27
	0.025	0.94	318.45	317.54	0.91	2.16
	0.05	0.96	311.36	311.35	0.01	0.01
	0.075	0.99	305.21	303.96	1.25	2.97
	0.1	1.01	300.67	299.45	1.23	2.91
	0.125	1.04	294.62	292.91	1.70	4.05
	0.135	1.05	292.51	291.30	1.21	2.87
Case B	0	0.93	336.81	334.99	1.83	4.01
	0.025	0.94	321.65	322.90	–1.25	2.75
	0.05	0.96	317.40	318.38	–0.99	2.16
	0.075	0.99	312.52	314.17	–1.65	3.63
	0.1	1.01	309.89	308.42	1.47	3.22
	0.125	1.04	297.33	295.29	2.04	4.48
	0.135	1.05	291.23	292.24	–1.01	2.22
Case C	0	0.93	339.69	337.09	2.6	5.51
	0.025	0.94	318.45	316.20	2.25	4.77
	0.05	0.96	311.36	311.52	–0.16	0.35
	0.075	0.99	303.21	301.89	1.31	2.79
	0.1	1.01	299.67	297.56	2.12	4.48
	0.125	1.04	295.62	293.79	1.83	3.87
	0.135	1.05	292.51	292.83	–0.32	0.69

Simulations aimed at studying the effects due to changes in geometry and comparison with the standards values

The mathematical model we implemented was used to investigate the thermal behavior of the soil in the path covering the linear heat sources depending on the geometric configuration of the excavation. On the basis of the mesh installed in the first part of the study, we recreated, always according to 2-D geometry, a generic underground excavation. By showing the geometry of the excavation we complied with the requirements of the current standards [24] that provide clear indications in relation to the depth of the installed cable compared to the level of the ground.

The type of installation that we designed was the one that the normative standard [17-19] defines as the "M1 type" for cables not fitted with metal reinforcements directly installed underground using additional mechanical protection, such as a flat plate.

The standard requires the minimum installation depth between the cable's support surface and the soil surface for the M type of installation is:
- category zero and 1 cable systems: 0,5 m,
- category 2 cable systems: 0,6 or 0,8 m, and
- category 3 cable systems: 1,0 or 1,2 m.

The geometry and dimensions of the excavation around the cable did not have a standard. A mesh geometry was chosen for the simulations that represented an excavation carried out "in a good workmanlike manner." The tendency at a worksite during installation is often to adhere strictly to the constraints imposed by law, and trying to save on the costs of anything that is not expressly imposed. This way of operating often means that the excavation varies in shape, and this affects the capability of heat dissipation into the surrounding soil.

Having defined the geometry that characterized the basic configuration of the excavation, the excavation was parameterized considering a series of varying sizes. Figure 3 shows the excavation in one of the most generic possible configurations. These that follow are the geometrical parameters we considered: h – the depth at which a cable is laid according to the works plan, d – the thickness of the sand backfill on top of the cable, c – the total thickness of the sand backfill, b – the width of the excavation, and D – the diameter of the underground cable.

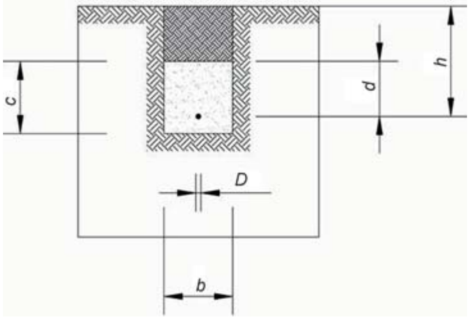

Figure 3. The excavation's geometrical parameters

In order to evaluate the effect of the excavation's geometrical parameters on the heat transfer and resistance of the soil around the cable, we made a series of simulations (in relation to backfilling with sand only) where we varied the geometry compared to the basic configuration:

Case 1: For similar excavations in terms of area and size, with the excavation completely filled with sand, we varied the depth of the cable in relation to the ground level, without going beyond the minimum permissible limits (0.50 m). For example, fig. 4 shows the basic configuration and the 1H configuration representing the geometric extremes. In intermediate cases the cable was traversed with a width of 0.1 m, thus defining the configurations of the A (base) to H;

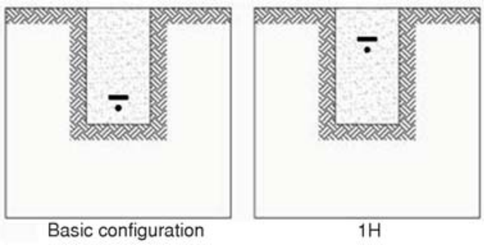
Basic configuration 1H

Figure 4. Extreme geometric configurations Case 1A (basic) and case 1H

Case 2: For similar excavations in terms of area, and without varying the ratio between the sizes of the excavation, keeping the position of the cable constant, we varied the sand layer over the cable, laying the earth removed during the excavation on top of the sand. We obtained different configurations in this case as well (from the basic A to M) as in fig. 5.

Case 3: For similar excavations in terms of area, we kept the cable at a constant depth compared to the ground level. We varied the excavations "c" and "b" dimensions, filling it with sand and the earth left over from the excavation; the earth laid on top of the sand until reaching the works level. We obtained different configurations in this case as well (from the basic A to H) as in fig. 6.

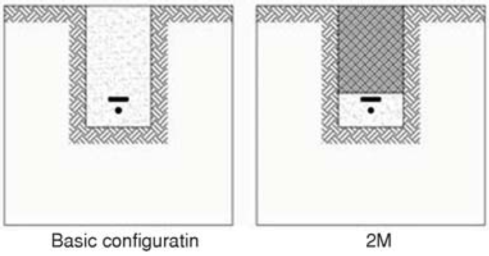

Figure 5. Extreme geometric configurations; Case 2A (basic) and Case 2M

Case 4: For similar excavations in terms of area and dimensions, we varied the depth of the cable compared to ground level, we varied dimensions "c" and "b" of the excavation filled with sand only. We obtained different configurations in this case as well (from the basic A to H) as in fig. 7.

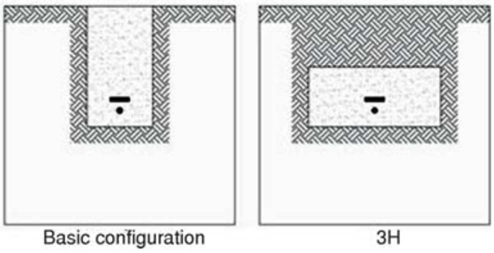

Figure 6. Extreme geometric configurations; Case 3A (basic) and case 3H

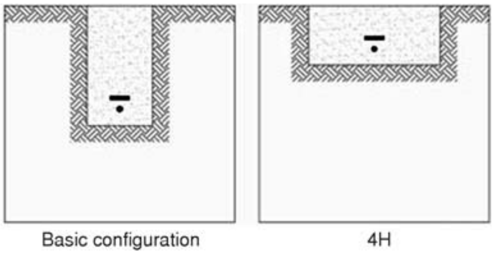

Figure 7. Extreme geometric configurations; Case 4A (basic) and Case 4H

Table 6 shows some geometric configurations values according to the geometric configuration examined.

We compared the obtained values by following the IEC standard for each of these configurations. In particular, the soil resistance was calculated according to the IEC standard using the equation:

$$R_{\text{norm}} = \frac{1}{2\pi} \rho \ln(u + \sqrt{u^2 - 1}) \tag{1}$$

We are going to show below the values and graphs of the thermal resistance of the soil in the cases analyzed and calculated by using FEM software following the IEC standard. As can be seen in Case 1 and 2 (tabs. 1 and 2; figs. 8 and 9) the resistance calculated using FEM software is always greater than that calculated according to the standard but the difference between the values tends to decrease every time the excavation configuration varies from the basic solution.

Table 6. Geometric parameters associated to the studied cases

Case		Dimensional parameter			
		h [m]	*d* [m]	*b* [m]	*c* [m]
Reference	1A = 2A = 3A = 4A	1.2	1.2	0.7500	1.3875
1	1B	1.1	1.1	0.7500	1.3875
	1C	1.0	1.0	0.7500	1.3875
	1D	0.9	0.9	0.7500	1.3875
	1E	0.8	0.8	0.7500	1.3875
	1F	0.7	0.7	0.7500	1.3875
	1G	0.6	0.6	0.7500	1.3875
	1H	0.5	0.5	0.7500	1.3875
2	2B	1.2	1.1	0.7500	1.2875
	2C	1.2	1.0	0.7500	1.1875
	2D	1.2	0.9	0.7500	1.0875
	2E	1.2	0.8	0.7500	0.9875
	2F	1.2	0.7	0.7500	0.8875
	2G	1.2	0.6	0.7500	0.7875
	2H	1.2	0.5	0.7500	0.6875
	2I	1.2	0.4	0.7500	0.5875
	2L	1.2	0.3	0.7500	0.4875
	2M	1.2	0.2	0.7500	0.3875
3	3B	1.2	1.1	0.8088	1.2875
	3C	1.2	1.0	0.8764	1.1875
	3D	1.2	0.9	0.9568	1.0875
	3E	1.2	0.8	1.0358	0.9875
	3F	1.2	0.7	1.1726	0.8875
	3G	1.2	0.6	1.3214	0.7875
	3H	1.2	0.5	1.5068	0.6875
4	4B	1.1	1.1	0.8082	1.2875
	4C	1.0	1.0	0.8764	1.1875
	4D	0.9	0.9	0.9568	1.0875
	4E	0.8	0.8	1.0358	0.9875
	4F	0.7	0.7	1.1726	0.8875
	4G	0.6	0.6	1.3214	0.7875
	4H	0.5	0.5	1.5068	0.6875

Table 7. Results of Case 1

Case		$R_{simulated}$	R_{norm}	$R_{simulated}/R_{norm}$
		[mkW^{-1}]		
1	A	4.730	2.764	1.711
	B	4.458	2.725	1.636
	C	4.202	2.681	1.567
	D	3.951	2.633	1.501
	E	3.700	2.580	1.434
	F	3.449	2.519	1.369
	G	3.195	2.449	1.305
	H	2.937	2.366	1.241

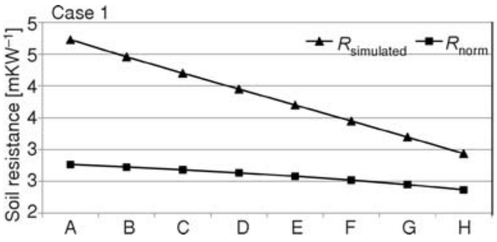

Figure 8. Case 1 – Variance in the thermal resistance of the soil: values obtained from simulations in comparison with those taken from the standard

Table 8. Results of Case 2

Case		$R_{simulated}$	R_{norm}	$R_{simulated}/R_{norm}$
		[mkW^{-1}]		
2	A	4.730	2.764	1.711
	B	5.169	2.764	1.870
	C	5.508	2.764	1.993
	D	5.814	2.764	2.103
	E	6.107	2.764	2.209
	F	6.394	2.764	2.313
	G	6.675	2.764	2.415
	H	6.970	2.764	2.522
	I	7.298	2.764	2.640
	L	7.642	2.764	2.765
	M	8.025	2.764	2.903

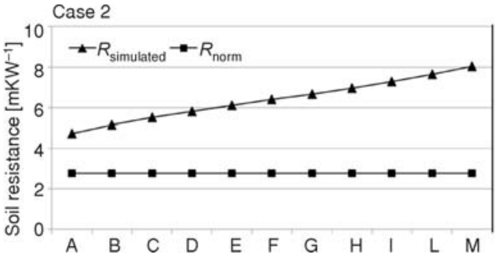

Figure 9. Case 2 – Variance in the thermal resistance of the soil: values obtained from simulations in comparison with those taken from the standard

Contrary to the previous cases, cases 3 and 4 has an increased $R_{simulated}/R_{norm}$ ratio the excavation configuration from the basic solution (tab. 9 and 10; figs. 10 and 11).

Table 9. Results of Case 3

Case		$R_{simulated}$	R_{norm}	$R_{simulated}/R_{norm}$
		[mkW^{-1}]		
3	A	4.730	2.764	1.711
	B	5.057	2.764	1.829
	C	5.292	2.764	1.915
	D	5.502	2.764	1.991
	E	5.706	2.764	2.064
	F	5.910	2.764	2.138
	G	6.129	2.764	2.217
	H	6.367	2.764	2.304

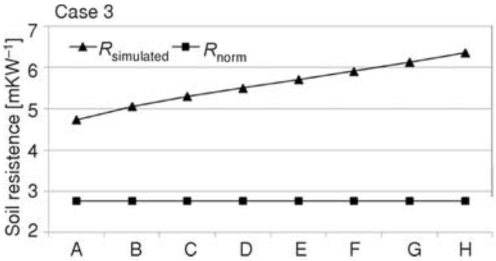

Figure 10. Case 3 – Variance in the thermal resistance of the soil: values obtained from simulations in comparison with those taken from the standard

Table 10. Results of Case 4

Case		$R_{\text{simulated}}$	R_{norm}	$R_{\text{simulated}}/R_{\text{norm}}$
		[mkW^{-1}]		
4	A	4.730	2.764	1.711
	B	4.380	2.725	1.607
	C	4.044	2.681	1.508
	D	3.727	2.633	1.416
	E	3.429	2.580	1.329
	F	3.154	2.519	1.252
	G	2.906	2.449	1.187
	H	2.685	2.366	1.135

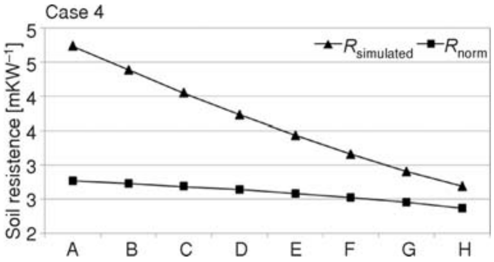

Figure 11. Case 4 – Variance in the thermal resistance of the soil: values obtained from simulations in comparison with those taken from the standard

Evaluation of the results and determination of the corrective correlation of the standard's values

While examining the results it is possible to conclude that the values of the resistance of the soil, according to the standard, are always lower than those determined by simulations (as already shown comparing experimental values resulting from laboratory tests, which we used to calibrate the mathematical model used). We have tried to find a correlation providing a corrective parameter for values calculated according to the standard, in order to bring the calculated values of soil resistance to values that are more in line with reality.

We decided to introduce only dimensionless parameters composed just of geometric sizes in relation to the excavation, and we therefore obtained as follows:

$$\frac{R_{\text{simulated}}}{R_{\text{norm}}} = f\left(\frac{c}{d};\frac{d}{D};\frac{h}{D}\right) = A\left(\frac{c}{d}\right)^{\alpha}\left(\frac{d}{D}\right)^{\beta}\left(\frac{h}{D}\right)^{\gamma} \tag{2}$$

The dimensionless parameters we chose, independent of each other, had the following ratios:

- *c/b* = ratio of the size of part of the excavation composed of the cable's bed of sand,
- *d/D* = ratio of the thickness of the layer of sand on top of the cable and the cable diameter, and
- *h/D* = ratio of the depth at which the cable was installed compared to the ground level and diameter of the cable.

We were able to determine the value of the correlation parameters, thanks to the method of Monte Carlo optimization, implemented with the software Matlab, the best fit of the data leads to the following numerical values for the constants expressed in formula (2):

$$A = 0.1218, \quad \alpha = 0.0443,$$
$$\beta = -0.3272, \quad \gamma = 0.9003$$

Thus the correlation provides the opportunity, while continuing to use the IEC standard, to determine a more realistic and cautionary value of thermal resistance in an area around an underground electrical cable. The maximum error is no more than 8%.

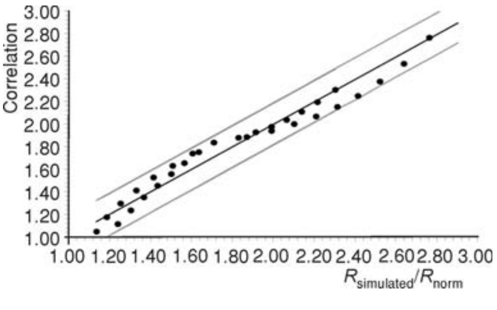

Figure 12. Variance trend of the soil resistance value calculated using the correlation compared to the value obtained through software simulations

Conclusions

This work was carried out to study the thermal field around an electrical cable using an FEM model and an appropriate and proper tested mesh. In this way we were able to verify the thermal resistance attributed to the soil according to current regulations. The study showed that several methods used in literature to evaluate the thermal behavior of a cable tend to overestimate the heat exchange with the soil, and consequently to underestimate overheating.

We observed that the IEC standard underestimates the resistance of the soil. In relation to the design phase, in order to be able to make the most suitable choice of cable to allow the disposal of the heat produced in Joules, it is necessary to carry out a correlation and correction of these equations. It has therefore been possible to propose the correction of these theoretical equations. Thanks to this correlation it is possible to furnish the design engineers with more precise information regarding the real conditions of the underground cables (during the setting phase) and the thermal resistance of the soil. This may help the engineers to choose more accurately for what concerns the cable sizing that have to be set underground in order to avoid a superheating.

The model we used is obviously applicable to other situations than those of an electrically charged cable, and they may concern, for example, gas pipelines or geothermal heat exchangers for heating pumps. The model can be used to obtain important information for optimal installations.

Moreover, prior knowledge of the thermal field generated at the surface may allow the calculation of the optimal depth of an excavation to prevent surface temperatures incompatible with surrounding agricultural crops.

Nomenclature

b – width of the excavation, [m]
c – total thickness of the sand backfill, [m]
c/b – ratio of the size of part of the excavation composed of the cable's bed of sand, [–]
D – external diameter of the cable, [mm]
d – the thickness of the sand backfill on top of the cable, [m]
d/D – ratio of the thickness of the layer of sand on top of the cable and the cable diameter, [–]
h – depth at which a cable is laid according to the works plan, [m]
h/D – ratio of the depth at which the cable was installed compared to ground level and diameter of the cable, [–]
L – distance of the axis of the cable from the surface of the soil, [mm]
u – $2L/D$, [–]

Greek symbols

Δ – maximum error in relation to the heat
ρ – thermal resistivity of the soil, [°CmW^{-1}]

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