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Experimental study of thermal field deriving from an underground electrical power cable buried in non-homogeneous soils

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HIGHLIGHTS

- Heat transfer of a buried cable has been experimentally studied on a scale model.
- Different configurations and thermal properties of the soil have been tested.
- Authors previously proposed a simplified model and obtained numerical results.
- Experimental results and numerical ones previously obtained were in accordance.

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ABSTRACT

The electrical cables ampacity mainly depends on the cable system operation temperature. To achieve a better cable utilization and reduce the conservativeness typically employed in buried cable design, an accurate evaluation of the heat dissipation through the cables and the surrounding soil is important. In the traditional method adopted by the International Electrotechnical Commission (IEC) and the Institute of Electrical and Electronics Engineers (IEEE) for the computation of the thermal resistance between an existing underground cable system and the external environment, it is still assumed that the soil is homogeneous and has uniform thermal conductivity. Numerical studies have been conducted to predict the temperature distribution around the cable for various configurations and thermal properties of the soil. The paper presents an experimental study conducted on a scale model to investigate the heat transfer of a buried cable, with different geometrical configurations and thermal properties of the soil, and to validate a simplified model proposed by the authors in 2012 for the calculation of the thermal resistance between the underground pipe or electrical cable and the ground surface, in cases where the filling of the trench is filled with layers of materials with different thermal properties. Results show that experimental data are in good agreement with the numerical ones.

1. Introduction

The thermal analysis of underground electrical power cables is important to determine their ampacity, i.e. their current carrying capacity. In fact, as the ampacity mainly depends on the cable system operation temperature, an accurate evaluation of the heat dissipation through the cables and the surrounding soil enables to overcome the conservativeness typically employed in buried cable design, and thus to achieve a better cable utilization. The traditional method adopted by the International Electrotechnical Commission (IEC) [1] and the Institute of Electrical and Electronics Engineers (IEEE) [2] for the computation of the thermal resistance between an existing underground cable system and the external environment is still based on the approximate equations derived in 1957 by Neher and McGrath [3] under the assumptions that the soil was homogeneous and had uniform thermal conductivity. This method was later improved by Sellers and Black [4], who proposed a correction procedure to take into account the eventuality that the soil used to fill the cable system location trench may have a thermal conductivity different from that of the mother soil. In the last two decades, the prediction of the temperature distribution around existing underground cable systems has been the subject of a number of numerical investigations, which were executed with the main aim of analyzing the cases of multiple cable system [5], of multi-layered soil [6], the effects of the thermal resistance between cable and retaining duct [7], the effects of the heat

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generation by eddy currents in the structural steels in the duct bank [8],the case of arrays of cables [9], the effect of the duct bank shape and size [10], of the thermal properties of different backfillings [11].

However, most of these works deal with too specific configurations or are characterized by a parametric approach: that limits considerably the use of their results for design purposes, especially for the calculation of the thermal resistance existing between a buried power cable and the ground surface, for different geometrical setups and thermal properties of the mother soil and materials used to fill the trench.

Heat transfer for horizontal cylinders is a deeply investigated matter also with reference to horizontal ground heat exchangers, linear or helical [12], or in horizontal loops of slinky coils [13]. In this fields topics of interest are the heat and mass transfer in wet porous media in the presence of evaporation–condensation [14], the pore-scale simulation [15], the moisture flow, evaporation and condensation effects on the self heating process of a wet porous medium [16], also in the presence of free convection [17].

In these cases however, main interest is focused on the use of ground as heat reservoir, especially on the matter of heat pumps use, and on energy exchanges with ground that could be obtained during a year, water diffusion in ground in different seasons, ground heat exchanges primarily in transient state.

In this study, moreover, focus of interest are especially heat exchanges between cable and outdoor air, through the soil; heat exchanges are of interest in the most unfavorable conditions concerning heat exchange and cable temperature, so in steady state, and in the most strictly conditions with reference to heat exchange, that is absence of humidity; after all it has been verified that in initially humid soils, often the cable operation dries out the surrounding soil [18].

Authors in a previous work [19] performed a comprehensive numerical study for the thermal resistance between a buried power cable and the ground surface calculation, for different geometrical setups and thermal properties of the soil and materials used to fill the trench, and an easy-to-apply correlating equation has been derived, spanning across sufficiently wide ranges of the independent variables, thus being helpful for design applications.

The proposed simplified method gives results consistent with the numerical one, with a standard deviation error of 3.6% and an error range percentage less than 10% with a 98% level of confidence. The main features of the simplified method proposed in Ref. [19] are shown in the Appendix.

Unfortunately, in this field there is a lack of experimental data; the existing data concern studies of electrical systems buried in homogeneous soils in steady-state [20] or transient state [21], the analysis of thermal conductivity of soils [22], and solid aggregates [23], or problems related to the humidity migration; determination of heat and mass transfer coefficients in moist soils [24], thermal instability in moist backfills [25], transient state heat and moisture transfer in porous media [26]. As authors know, there is no specific research about non-homogeneous soil cases.

Aim of this work is to provide a scale model of a buried electric cable, with different geometrical setups and thermal properties of the mother soil and materials used to fill the trench, in order to experimentally verify, through an experimental session, the adequacy of both the numerical model and the simplified method proposed in Ref. [19].

2. Experimental set up

A 50 mm diameter cable placed at a depth of 1.25 m in a trench 1.5 m deep and 0.8 m width, has been simulated at a 1/10 scale. The excavation is practiced in the ground and can be filled with layers of different materials.

In detail (Fig. 1), the cable is simulated through a stainless steel AISI 316 tube, 5 mm outer diameter and 0.25 mm thick, 1.4 m long. The material that simulates the soil is placed in a box made of 15 mm thick plywood; the box is 1.5 m long in the cable direction, and 1.9 m width (the cable is placed in the middle, and the box is 0.95 m wide at each side). The depth of the body box is equal to 0.35 m. On the outer face of the bottom and of the box sides, a sheet of polystyrene foam insulation thickness of 5 cm is applied.

The trench is simulated by a further container, made of plywood 4 mm thick, 1.5 m long, 8 cm wide and 15 cm deep. It is equipped with two baffles placed at a distance of 5 cm from the ends. In this way two cavities have been created, for the transit of the electrical wires used to heat the tube and the thermocouples, used to measure the tube temperature and the temperature in various points of the excavation, as more fully described in the following.

The tube is placed at a distance h_c from the surface equal to 13.5 cm, and is supported by the baffles of the container and by two intermediate diaphragms.

As indicated in Ref. [19], and with reference to Fig. 2, the ratio between the thermal resistance between the tube and the surface of the ground R_{CG} in the case of field laterally and below limited by adiabatic surfaces respectively $x = x^*$ and $y = y^*$, and the ideal value $R^{(0)}{}_{CG}$ relating to a field below and laterally unbounded depends on the ratios y^*/h_c and x^*/h_c with the trends shown in Fig. 2.

In the realized test section it is $y^*/h_c = 2.6$ and $x^*/h_c = 7.6$; with these values, the ratio $R^{(0)}{}_{CG}/R_{CG}$ value is about 0.97 and then with an error of the order of 3%.

The trench is equipped with five k-type thermocouples (wire 0.3 mm diameter), whose measure joints are put in the vertical plane passing for the centerline of the tube, on his half length, over the tube, at fixed distances from the tube (25 mm, 50 mm, 75 mm, 100 mm, 125 mm).

The electrical wires are insulated with glass fiber. The joint is obtained through the wires twisting (length 8–12 mm). To place the thermocouples in a repeatable position, a formwork has been

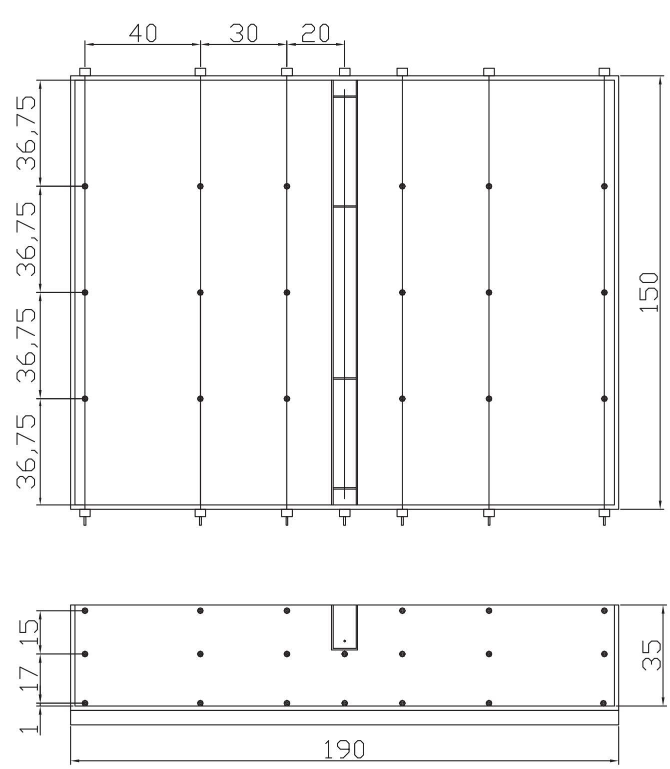

Fig. 1. Test section and thermocouples layout.