Effects of Thermal and Electro-osmotic Flux on Grounding Electrodes

I.F.R.Costa[1], M.C.Barbosa[1], A.O.Costa Neto[2]

[1] *COPPE/UFRJ, Rio de Janeiro, RJ, Brazil*
[2] *UFVJM, Teófilo Otoni, MG, Brazil*
iara@coc.ufrj.br, mclaudia@coc.ufrj.br, alcino.neto@ufvjm.edu.br

Abstract

The continuous adequacy of the electrical service, maintenance, and safety is based on the importance given to the project and the construction of the grounding networks. Depending on the properties of the soil and in case of failure in grounding, the electrode may be damaged, thus preventing the use of the transmission system, in addition to possible human losses. This work intends to present the perspectives of the research on the performance of the soil in the vicinity of an active grounding system, considering the behavior of the electrical potential and its correlations with electro-osmosis and thermal flow. A hypothesis with homogeneous soil was simulated using the software COMSOL Multiphysics® version 5.5., considering an electrode as rod in a vertical position located 1m deep from the ground level. The results show that the most critical effects are restricted to the immediate vicinity of the electrode.

Keywords: electrodes, electro-osmosis, thermal flow, Joule effect.

Introduction

Over the years, global electricity production has grown steadily since 1974, except between 2008 and 2009, when the global financial crisis caused a significant drop in production. In 2018, final consumption in the world in relation to this system reached 22315 TWh, 4.0% higher than 2017 [1].

One of the essential components of the electrical system is the grounding network. In any mode of electric energy transmission, the ground can be used as a current return path, so the stations must have a grounding system that can support currents with considerable values [2].

The grounding applications are designed to meet varied electrical requests, which range from occurrences in direct current or close to industrial frequency or even quick phenomena such as atmospheric discharge [3]. Due to safety and environmental considerations, there is an interest in the dynamics of the soil around the electrode.

A considerable number of studies show the development of the electrical potential in the soil, around the electrode, however, studies on phenomena such as electro-osmosis are still limited to the grounding dynamics, as well as the thermal flow for transitional behavior. Both flows stimulate the reduction of local humidity, which can cause, in extreme cases, thermal instability, and as a consequence, failures in the grounding electrode, making the system inoperable.

The present work proposes to establish the basis for a model that represents the risk of dryness of the soil along the area around of a vertical grounding electrode belonging to the electrical system, considering the coupled study of the electro-osmotic flow and the flow due to the thermal gradient, from the COMSOL Multiphysics program, considering modules and interfaces necessary to solve the problem.

Theory

Grounding systems

Empirical data indicates that about 80% of all electrical interruptions in the world are attributed to ground faults [4]. In turn, the grounding is constituted, fundamentally, of a structure buried in the ground, in order to guarantee good electrical contact with the environment through grounding electrodes. Grounding networks, in turn, can consist of only one electrode or a set of electrodes.

The soil must be characterized as a semiconductor, while the electrode is a pure conductor. There are grounding systems that use sea electrodes to provide an electrical return path, as reported by [5]. For [6] the main components responsible for the behavior of the grounding system under abnormal conditions can be classified into three categories: the connection between the power system and the electrodes; the grounding configuration, including the type of electrode, the material used, and the dimensions; and finally, the characteristics of the soil where the electrodes are installed.

For the last component, it requires detailed studies on the electro-osmotic, electrical and thermal phenomena considering a transient and dynamic behavior of the process of raising the soil temperature, from the continuous injection of the electric current in the electrode.

Electro-osmotic flow

When an electric field is established inside a saturated soil mass, the relative movement of the liquid phase in relation to the solid phase tends to occur, a phenomenon known as electro-osmotic flow.

The movement of the liquid phase of the system occurs due to the effect of the electric field established between the electrodes on the ions present in this phase. The moving ions carry the water molecules that hydrate them and exert a drag force on the other water molecules around them, causing the coupled movement of these water molecules. In general, water flows from the anode to the cathode, as shown in Figure 1.

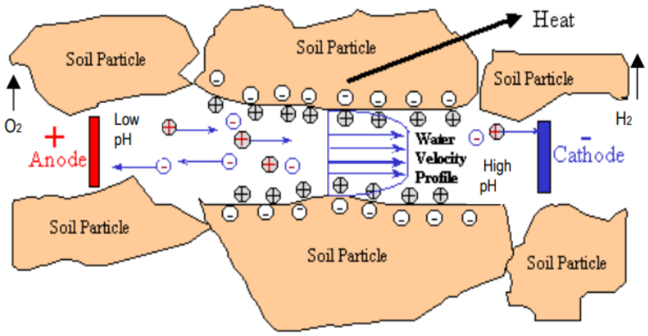

Figure 1. Graphical representation of electro-osmosis [8].

The electro-osmotic flow will occur if the material has an acceptable coefficient of electro-osmotic permeability *(ke)*, and if an effective voltage gradient can be maintained across the material [7].

The traditional use of electro-osmosis in civil engineering is linked to the thickening of fine soils, remediation, as well as the thawing of soils. While for the aforementioned applications, electro-osmosis is a fruitful process, however in grounding electrode designs, its use must be avoided or minimized [8].

With the flow of water due to the electro-osmotic process, the humidity around the electrode is reduced, to the detriment, the resistivity of the soil increases, leading to a greater dissipation of heat while the electrode is operating.

Thermal flow

The current injected through the electrode results in soil heating, essentially due to the heat dissipation by Joule effect. In turn, the heat flow through the ground is basically conducted by conduction and convection [9]. The radiation flow is irrelevant, except for superficial soils [10]. The conduction is significant in the solid phase of the soil since the values of thermal conductivities for mineral soils are much higher than those for water and air. As for convection, this is significant in the presence of significant water or airflow rates, as can be seen in sandy soils or in boulders, or even in determining the temperatures around the analyzed soil.

Methods

Conceptual Model

Based on the considerable importance of the role that grounding electrodes play in the electrical transmission system, it is necessary to know the elements that affect their performance, in terms of geotechnical requirements, using the COMSOL Multiphysics software, version 5.5.

The injection of current in the soil raises the temperature in the vicinity of the electrodes by Joule effect and promotes the electro-osmotic flow in the direction of the electric field. In the electrode acting as an anode, in particular, the flow by electro-osmosis causes the soil to dry out. The two phenomena together remove moisture from the soil near the electrode, increasing the resistivity of the ground, contributing to the increase in temperature and possible vitrification of the soil and drying of the electrode.

The electro-osmotic flow (*qe*) occurs radially, depending on the electric field generated by the electrode. In detriment, the water and steam flow originated by the thermal gradient produced by the Joule effect, occur not only radially, but also vertically, since there is a temperature difference between the heated region corresponding to the electrode and the layers of overlying and underlying soil, as shown in Figure 2.

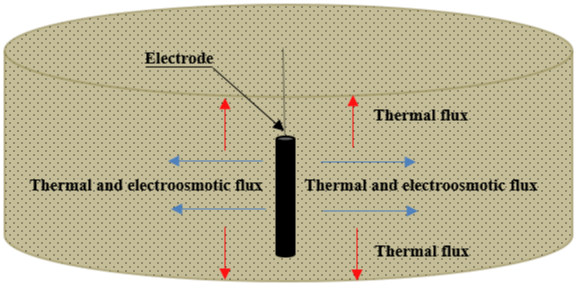

Figure 2. Adopted geometric model.

For the model, a cylindrical geometry was adopted for its reproduction, with a hollow element simulating the vertical electrode, through which the axis of symmetry passes. The soil domain, in its turn, has a diameter of 10.0m and 5.0m in depth. The problem uses the electrode symmetry axis, as it helps to reduce the simulation time, as shown in Figure 3.

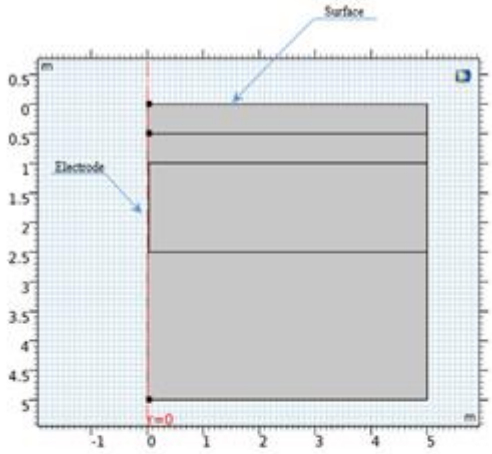

Figure 3. COMSOL geometry of the problem space.

Some premises were adopted throughout this work:
- homogeneous soil;
- 2D axisymmetric geometry;
- continuous electric current;
- horizontal surface;
- vertical confined electrode;
- electric field in steady-state;
- electrode functioning as an anode;
- Joule effect due to the passage of electric current through the porous medium;
- flow caused by electro-osmosis

In this case, the properties of electrical conductivity, heat capacity, and thermal conductivity as a function of temperature, according to equations developed by COMSOL for soils, present in the program's material library.

For the model, the *Batteries and Fuel Cells* Module were adopted to take advantage of the Heat Transfer in Porous Media interface, as well as the main COMSOL package, using the multiphysics Joule Heating interface and the insertion of equations involving electro-osmosis.

Governing Equations

The first phenomenon considered is Joule heating, in which the temperature increases due to the resistive heating of an electric current. The laws that govern the process are demonstrated in equations 1 and 2.

$$Q_e = JE = (\sigma E)E = \sigma E^2 \tag{1}$$

$$E = -\nabla V \tag{2}$$

Q_e is the source of electromagnetic heat, E is the strength of the electric field, J is the current density, σ is the electrical conductivity, and V the electrical potential.

For heat transfer in the soil, Darcy's law is associated with solving the temperature field in every domain. The governing equations are given in 3, 4, and 5.

$$(\rho C_p)_{eff} \frac{\partial T}{\partial t} + \rho C_P u \nabla T + \nabla q = Q_e \tag{3}$$

$$\left(\rho C_p\right)_{eff} = \theta_p \rho_p C_{p,\rho} + \left(1 - \theta_p\right) \rho C_p \tag{4}$$

$$q = -k_{eff} \nabla T \tag{5}$$

Where ρ is the specific mass of water, $C\rho$ is the thermal capacity of the same fluid, T is the temperature, t is the time, u is the velocity field, q is the heat flow by conduction, $(\rho C_\rho)_{eff}$ is the volumetric capacity of effective heat, $\rho_{p,}$ $C_{\rho,p}$ e θ_p represent the specific mass, the thermal capacity, and the volume of the solid fraction of the soil.

In its turn, k_{eff} is the effective thermal conductivity, given by Equation 6.

$$k_{eff} = k_p^{\theta_p} k^{1-\theta_p} \tag{6}$$

k_p and k represent, respectively, the thermal conductivity of the solid material in the medium and water.

In this case, as the soil is initially saturated, the fluid is represented by the water that occupies the middle pores. It is noticed that the multiphysics coupling between the electric and the heat occurs in Equation 3, starting from Q_e.

Continuing with the proposal of this article, the electro-osmotic velocity (Equation 7) is calculated from the Helmholtz-Smoluchowski ratio [13]:

$$u_{eo} = \frac{\varepsilon_p \varepsilon_w \zeta}{\mu \tau} \nabla V \tag{7}$$

where u_{eo} represents the interstitial velocity due to electro-osmosis, εp the porosity, εw the water permittivity, ζ the zeta potential of the soil, μ is the dynamic viscosity of the fluid and τ the tortuosity factor.

The first part of the equation described above is equal to electro-osmotic conductivity (k_e), as [10] considering the tortuosity factor equal to one unit. Equality is represented in Equation 8.

$$k_e = \frac{\varepsilon_p \varepsilon_w \zeta}{\mu} \tag{8}$$

Boundary conditions and initial conditions

For the distribution of electrical potential in a homogeneous soil **[12]**, Equation 9 was inserted along the contour that represents the electrode ($0 \leq r \leq 0.025$ and $1 \leq Z \leq 2.5$m).

$$V(\mathrm{r}, \mathrm{z}) = \frac{\rho I}{4\pi L}\left(\ln\left(\frac{L + h - z + \sqrt{r^2 + (L + h - z)^2}}{h - z + \sqrt{r^2 + (h - z)^2}}\right)\right) + \left(\ln\left(\frac{L + h + z + \sqrt{r^2 + (L + h + z)^2}}{h + z + \sqrt{r^2 + (h + z)^2}}\right)\right) \tag{9}$$

In the equation, ρ is the electrical resistivity in the soil, I is the current injected into the electrode, L is the length of the electrode, h represents the depth of burial of the same element, and finally, r and z represent the cylindrical coordinates, the distance being vertical z originates from the soil surface.

In the contour of the ground in contact with the surface, the electrical insulation condition was admitted, in the symmetry axis, the axial symmetry condition and in the other contours, the ground potential (V = 0V). The initial temperature is 20ºC throughout the soil.

Simulation Results

Table 1 summarizes the main parameters adopted in the modeling.

Table 1. Values of the adopted parameters.

Parameters	Values
Electrical resistivity	100 Ω.m
Porosity	0.5
Zeta potential	0.1V
Water permittivity	$7.1011 \mathrm{x} 10^{-10}$ F/m
Dynamic water viscosity	0.001 Pa·s
Volume of the solid fraction of the soil	0.5
Electric current	100A

The distribution of electrical potential in the soil mass around the electrode is shown in Figure 4, for an injected current of 100A and electrical resistivity of 100Ω.m (or electrical conductivity of 0.01S/m).

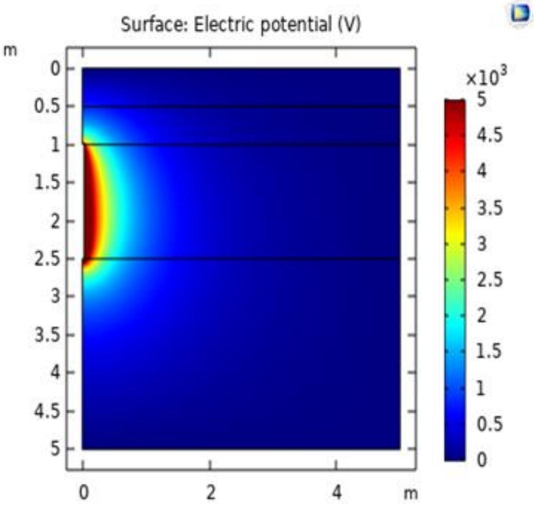

Figure 4. Distribution of electrical potential (Volts).

It is noticeable that the values generated are extremely high in the vicinity of the electrode (more than 5000V), and that the total electrical current would have to be distributed over a greater number of electrodes.

Figure 5 represents the 1D plot, of the same potential along the radial distance.

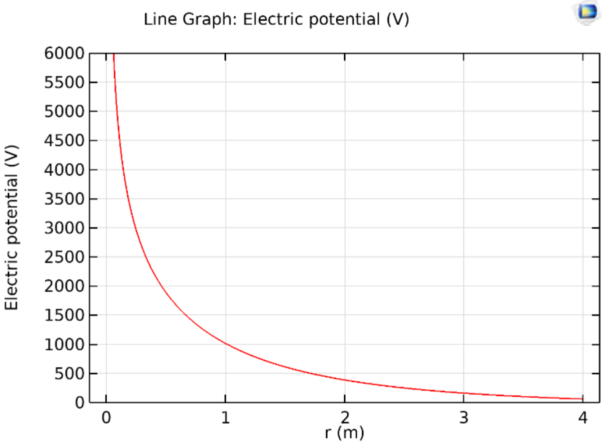

Figure 5. Distribution of electrical potential along the r coordinate.

It can be seen that there is a rapid decay of the potential with distance and that from 3m the potential on the ground stabilizes to values less than 100V.

In terms of temperature, Figure 6 shows the distribution in the vicinity of the electrode, with the parameters indicated in Table 1, after 30 days of continuous operation of the electrode.

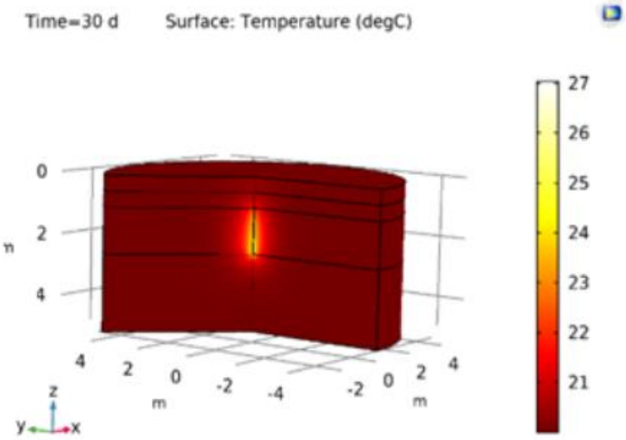

Figure 6. Temperature distribution in ºC at 30 days.

It is observed that the temperature varies in the radial distances up to 1m from the electrode, where $1 \leq z \leq 2.5$m, due to the heating by the Joule effect.

Figure 7 reports the temperature evolution for the point at the bottom base of the electrode, considering the coordinates r = 0m and z = 2.5m

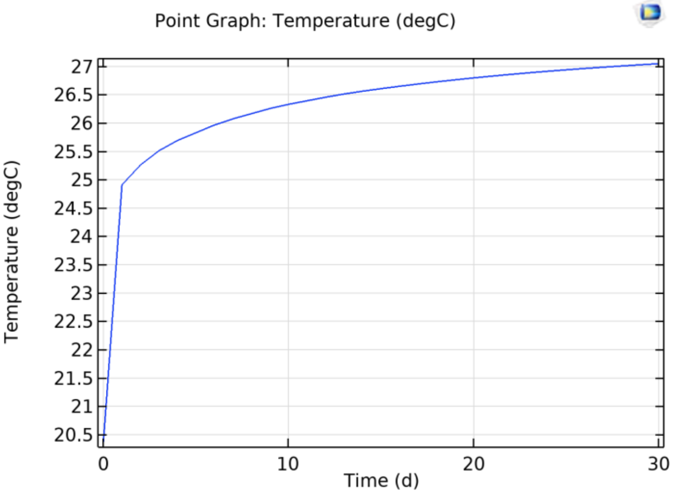

Figure 7. Evolution of temperature over time for point r = 0m and z = 2.5m.

The point in question is that where temperature values were the highest throughout the model, reaching 27ºC, and stabilizing around one month.

In turn, Figure 8 illustrates the heat flow associated with the conduction between the solid particles of the soil for the radial distance.

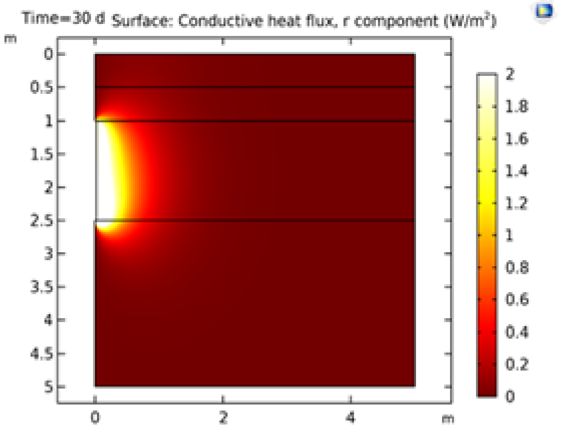

Figure 8. Heat flow due to driving at 30 days.

As expected, the conductive flow is greater around the electrode, reaching 2W/m². Conduction is especially necessary to achieve thermal equilibrium in the medium and it is most representative in solid soil particles.

Based on the electrical potential and soil properties, Figure 9 shows the velocity associated with the electro-osmotic flow.

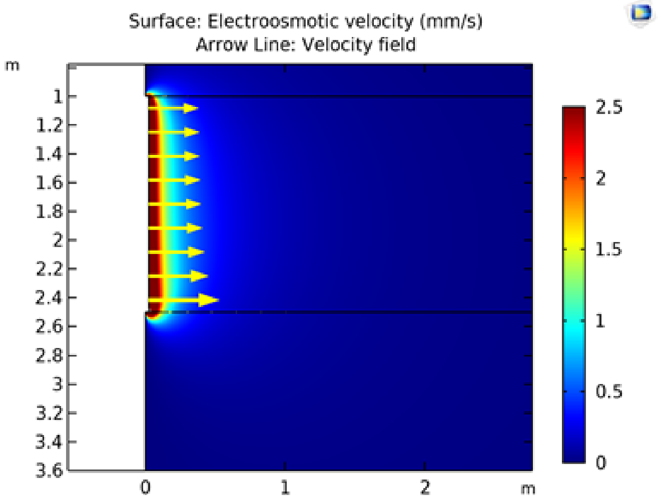

Figure 9. The electro-osmotic velocity generated by the establishment of electrical potential.

It can be seen that the electro-osmotic flow follows the contour of the electrical potential depicted in Figure 4, characterizing its highest rate at the lower base of the electrode.

Figure 10(a) and 10(b) show the electro-osmotic flow along the soil depth, respectively, considering r = 0.1m and r = 1.0m.

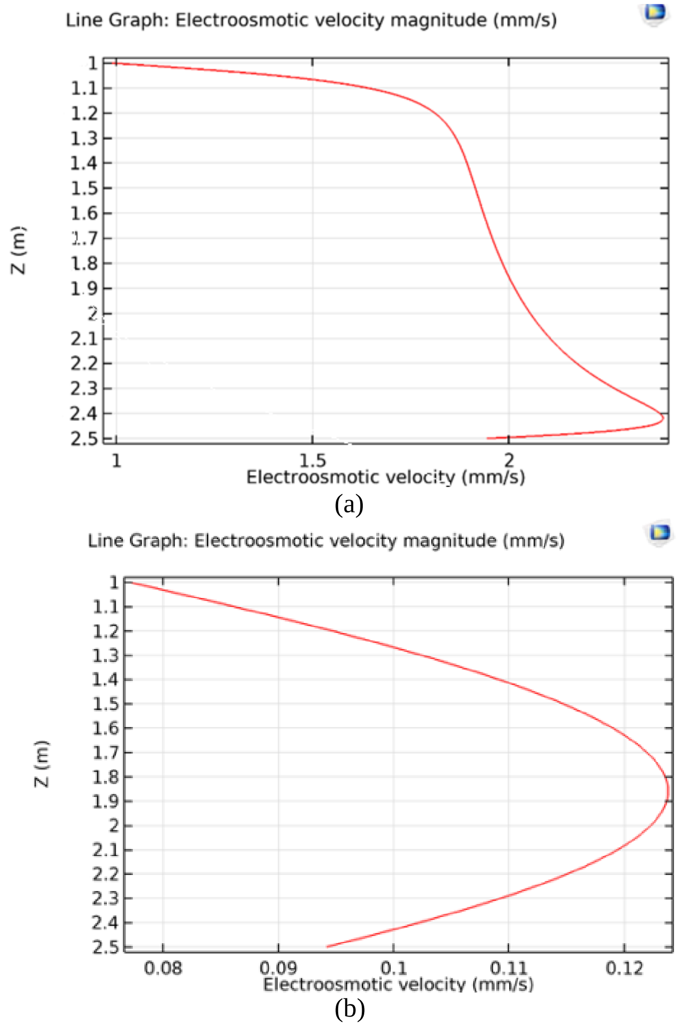

Figure 10. Electro-osmotic velocity (a) distribution with depth at a distance of r = 0.1m; (b) r = 1.0m.

It is interesting to note that close to the electrode (r = 0.1m) the electro-osmotic velocity is higher at its lower base (about 2.5mm/s). For more distant points (r = 1.0m), the velocity value reduces considerably (about 0.125 mm/s) as already reported by [9], with a tendency in-depth close to the central region of the electrode.

Conclusions

The coupled analysis of the electrical, thermal, and hydraulic phenomena involved proves the disturbance caused by the electric current in the vicinity of the grounding electrode. The most critical effects are restricted to the immediate vicinity of the electrode. It is worth noting that low values for electrical current were used, as well as electrical resistivity. Both parameters can reach very high values, considering the phenomena of lightning and tropical soils. It is still necessary to evolve with work for unsaturated soils, based on the Richards Equation present in *COMSOL's Subsurface Flow Module*, and the variation of soil properties with humidity, activities that are in progress.

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