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3D ANALYSIS OF PIPELINE WITH CATHODIC CORROSION PROTECTION

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Abstract. ***Natural gas is an indispensable resource for human life. Its transport is usually done through underground pipelines. Due to the environment in which they are placed, the pipelines are subjected to a continuous process of corrosion. This paper aimed a 3D numerical analysis using specialized software (COMSOL Multiphysics) to study several parameters that influence the corrosion of underground pipelines. Starting from real geometric and environmental data, a comparative analysis was performed, considering the pipeline coating (e.g., with HDPE - high-density polyethylene), the placement of the cathode protection electrode, and the soil conductivity near the pipeline. The results confirm the need to cover the pipelines and can be a starting point for choosing the final configuration of the cathodic protection system.***

Keywords: Numerical analysis, Pipeline corrosion, Cathodic protection.

1. INTRODUCTION

The gas distribution network is the human body-like arteries for any country. As can be seen in daily activities, natural gas is an indispensable resource for human society. Therefore, the maintenance of this system is an essential aspect of any country's strategy [1-3].

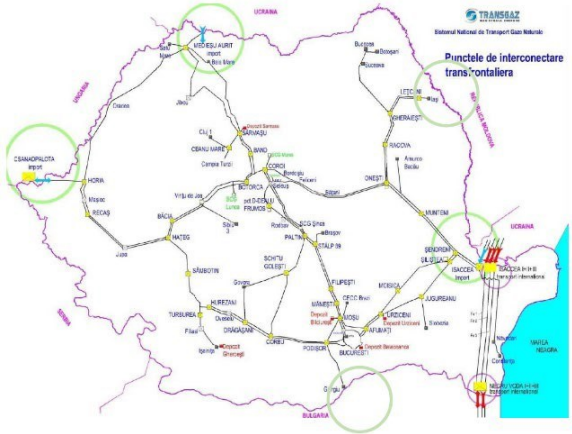


Figure 1. NTS cross-border interconnection points and international natural gas transmission pipelines in south-eastern Romania [4].

On the Romanian territory, TransGaz deals with the gas transmission and distribution part (Figure 1). It aims to develop the system by 2026 by making all the corridors and interconnections presented on this map: eastern corridor, central east-west corridor, north-south corridor, south-east-west corridor (BRUA: Giurgiu - Nădlac), southern interconnector-East, northwest interconnector, international transport corridor. Also, there can be seen the communication nodes with neighboring countries (Moldova, Ukraine, Bulgaria and Hungary) [4].

In addition to the high costs of building such a network, the maintenance part causes a significant increase in the value of such a system. According to the report of National Association of Corrosion Engineers (NACE) in 2016, about 2.5 trillion USD is the cost of pipeline steels corrosion in this industry, which is 3.4% of the world's gross domestic product (GDP) [5]. A recent report [6] indicates that the largest share of maintenance costs for underground gas and oil pipelines is due to their corrosion (Figure 2).

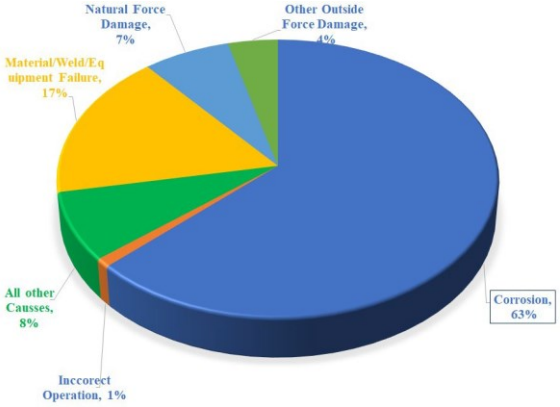


Figure 2. Causes of gas transmission pipeline significant incidents [6] and [7].

In this area, all aspects are standardized, and the maintenance of transmission lines is ensured in various service areas. Thus, a series of aspects are presented in the European standard EN ISO 21809-1:2018, second edition, entitled "Petroleum and natural gas industries - External coating for buried ad submerged pipelines used in pipeline transportation systems/Part1 - Polyolefin coatings (3 layers PE and 3-layer PP)" [8].

The main causes of pipeline corrosion are physical factors, chemical factors, and environmental factors. The former can be represented by structural properties (such as material properties, design factors, inclusions, etc.) and product properties (such as temperature, pressure, flow rate, etc.). As chemical factors one can consider

dissolved solids, organic and inorganic acids, microorganism, hydrocarbons and so on. Finally, as environmental factors one can include soil composition, temperature and moisture levels, nature of operating area [9].

These cumulative aspects clearly lead to the idea that preventing and reducing corrosion of underground gas transmission pipelines is a key issue in this area [10-11]. Previous studies [12-14] have been the starting point for this work. The paper deals in Section 2 issues related to materials encountered in such pipelines, as well as the main relationships that govern the corrosion process. The next three sections are dedicated to 3D numerical analysis using COMSOL Multiphysics of the influence of the pipeline protection layer, the placement of the electrode near the pipeline, and the different soil combinations with distinct conductivities around the system, respectively.

2. MATERIALS AND METHODS

According to the general properties, the general-purpose carbon steels are usually used for the construction of pipelines. These materials are commonly used in the construction of pipelines and are steels with a carbon content of up to 0.6%, not alloyed or weakly alloyed with Mn (OL 44) or Mn, Si and V (OL 52) [15]. The current material used for gas pipelines is OL 37, which has a breaking strength of 360-440 N/mm^2 and a chemical composition including 0.2% C, 1.4% Mn, 0.045% P and 0.045% S (for EN S235JR (STAS OL) 37.2k), and 0.17% C, 1.4% Mn, 0.035% P and 0.035% S (for the EN S235J2 sort (STAS OL 37.4k), respectively [16].

The corrosion process of a metal pipeline is based on two chemical processes [17]:

$$M_M \rightarrow M_{aq}^{2+} + 2e_M^- \quad (1)$$

- cathodic reduction of oxidants:

$$2Ox_{aq} + 2e_M^- \rightarrow 2Red(e_{redox}^-)_{aq} \quad (2)$$

where M_M is the metal in the state of metallic bonding, M_{aq}^{2+} is the hydrated metal ion in aqueous solution, e_M^- is the electron in the metal, Ox_{aq} is an oxidant, $Red(e_{redox}^-)_{aq}$ is a reductant, and e_{redox}^- is the redox electron in the reductant [17].

These reactions represent processes of electric charge transfer that take place at the metal interface - the aqueous solution, so they are dependent on the surface potential that essentially corresponds to what is called in electrochemical terms the electrode potential of metals. Thus, we can rewrite the combination of the corrosion equation with the expression [16]:

$$M_M + 2Ox_{aq} \rightarrow M_{aq}^{2+} + 2Red(e_{redox}^-)_{aq} \quad (3)$$

According to the standard EN ISO 21809-1: 2018 [8], the coating of underground gas pipelines is made with various types of materials (Figure 3). Coating classes B and C can be selected due to the higher mechanical properties for a specific purpose of rather than maximum operating temperatures.

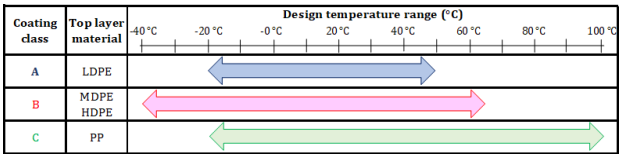


Figure 3. Coating classes and design temperature range, according to [8].

The thickness class of the coating shall be selected by the buyer and the end user based on the installation and service conditions and the dimensions of the pipe. The materials of the upper layer are LDPE - low-density polyethylene, MDPE - medium-density polyethylene, HDPE - high-density polyethylene, PP - polypropylene. According to the same standard [8], the thickness of the insulation layer depends on the installation conditions and the nature of the soil in which the pipeline is buried. Thus, Class 1 or lower thickness is defined, which can only be used for easier installation / laying conditions (sandy soils, prepared filling with selected materials). Class 2 can be applied for standard conditions (for example, clay soils, native soil fillers, without coarse materials). Class 3 or higher may be applied at least for more severe environments and installations and layer conditions (e.g., offshore, rocky soils).

In the case of systems managed by TransGaz, the pipeline is insulated with HDPE, and for the filler welds we use heat-shrinkable polyethylene sleeves. The insulation thicknesses differ depending on the weight / linear meter of the pipeline, as it is indicated in Table 1.

Table 1. Minimum dimensions standard for TransGaz pipelines.

Pipe mass [kg/lm*] / location class	Pipe diameter [mm] / wall thickness [mm]	Minimum insulation thickness [mm]
Natural gas transmission pipeline		
105.57 kg/lm / class 1b	600 mm / 7.1 mm	3.1 mm (B3)
130.47 kg/ lm / class 2	600 mm / 8.8 mm	3.5 mm (B3)
162.49 kg/ lm / class 3	600 mm /11.0 mm	3.5 mm (B3)
184.19 kg/ lm / class 4	600 mm /12.5 mm	3.5 mm (B3)
Protective tube		
188.25 kg/lm	800 mm / 9.5 mm	3.5 mm (B3)
235.10 kg/lm	800 mm / 11.9 mm	3.5 mm (B3)
18.18 kg lm	150 mm / 4.5 mm	2.7 mm (B3)
28.23 kg/lm	150 mm / 7.1 mm	2.7 mm (B3)

**kg/lm = kilogram per linear meter.*

High-Density Polyethylene (HDPE) is a thermoplastic polymer made from the ethylene monomer. It is sometimes called "alcaten" or "polyethylene" when used for HDPE pipelines. With a high strength-to-density ratio, HDPE is used in the production of plastic bottles, corrosion-resistant pipes, geomembranes, and plastic lumber. HDPE is usually recycled and has the number "2" as the resin identification code. HDPE is resistant to many different solvents, so it cannot be glued. Pipeline joints must be made by welding. The physical properties of HDPE may vary depending on the casting process that is used to make a specific sample. To some extent, a determining factor is the international standardized test methods used to identify these properties for a given process [18-19].

Considering the design process proposed in this paper, some properties of this material are important and can be seen in Table 2 [20].

Table 2. Electrical properties of the HDPE insulation.

Electrical property	Accepted range
Electrical resistivity	$10^5 – 10^{17}$ [Ω·cm]
Dielectric constant	2.35 – 2.45
Dielectric strength	16 – 18 [kV/mm]
Dissipation factor	0.0002 – 0.02

For the simulations, a 3D model was used (Figure 4), considering a 2 meters long pipeline buried 1 meter below the soil level. The pipeline has 60 cm diameter, and the origin of the system is considered the center of the pipeline. The electrode is placed in the soil at different distances to the pipeline (Figure 5). In this model two benchmarks for comparison were considered – a line between the pipeline and the electrode in the soil, and a line on the ground level, respectively.

In COMSOL [21] was selected an Electrochemistry problem, Primary Current Distribution Subdomain and Stationery filed. In this kind of problem, the charge transfer in the electrolyte is assumed to obey Ohm's law [21]. Here, two dependent variables are defined:

- for electrode

$$J_s = -\sigma_s \nabla \Phi_s, with\ \nabla \cdot J_s = 0, \quad (4)$$

- for electrolyte

$$J_l = -\sigma_l \nabla \Phi_l, with\ \nabla \cdot J_l = 0, \quad (5)$$

where σ denotes the electrical conductivity (linear medium), Φ the electric potential and J the current density. The index s represents the electrode and l the electrolyte.

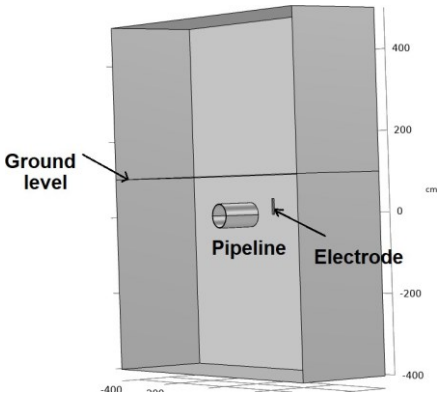


Figure 4. General geometry of the modeled system.

The initial values for both potentials are considered 0. The field source is the electrode characterized by fix density of electrical current (J_l = 0.02 A/mm^2). To simulate the installed electrochemical potential on the pipeline, this one is considered with J_s = - 0.02 A/mm^2.

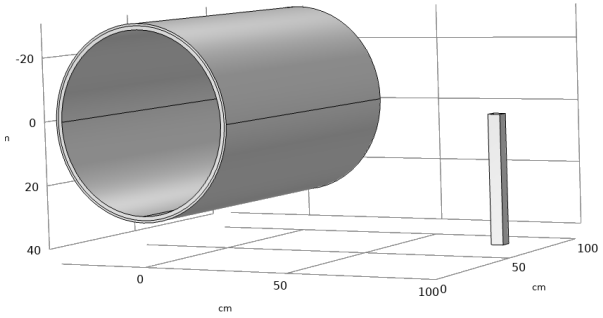


Figure 5. 3D geometry of the pipeline and the electrode.

To emphasize the vectors for the electrical current density in Figure 6 is represented these vectors in a 2D representation. The simulations from this paper cover a number of 65936 elements solved in 1.2 seconds. But, for complex problems even 1152975 elements were used, and the simulation time increases to 12.4 seconds for the same processor.

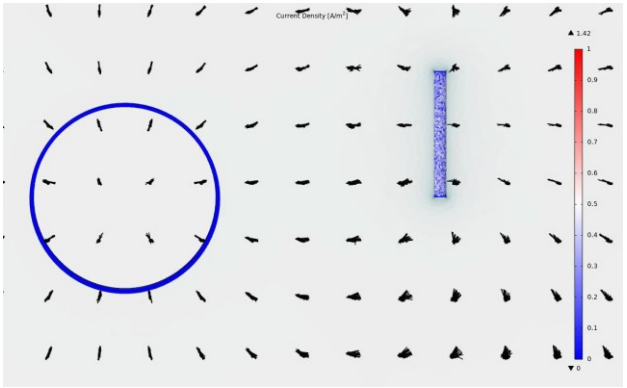


Figure 6. Representation of vectors for the electric current density.

3. INFLUENCE OF THE PIPELINE PROTECTION

The first aspect of this study was to find out the

influence of the HDPE layer on the buried pipeline. Thus, three situations were studied: the uncovered pipeline, the pipeline covered with 3.5 mm insulation, and covered with a 5 mm layer, respectively. The first and third cases are presented in terms of electrical potential in Figures 7 and 8, respectively.

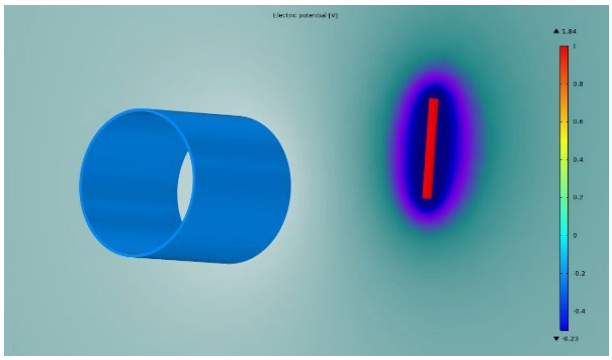


Figure 7. Electrical potential for uncovered pipeline.

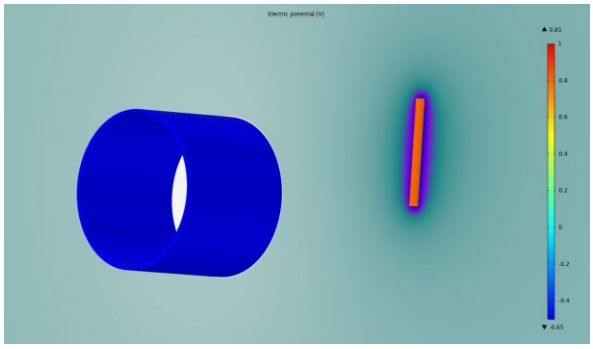


Figure 8. Electrical potential for a 5 mm insulation layer.

A comparison of the electric potentials for the analysed situations was also made. In Fig. 9 this comparison made at ground level can be followed, while in Fig. 10 the result can be followed along a line between the pipe and the electrode, through the ground, at the level of the cathodic protection system (one meter below the ground level).

It can be seen from both images (Figures 10 and 11) that the presence of this protective layer on the pipe leads to a reduction in the values of the electric potential both in the soil and on its surface.

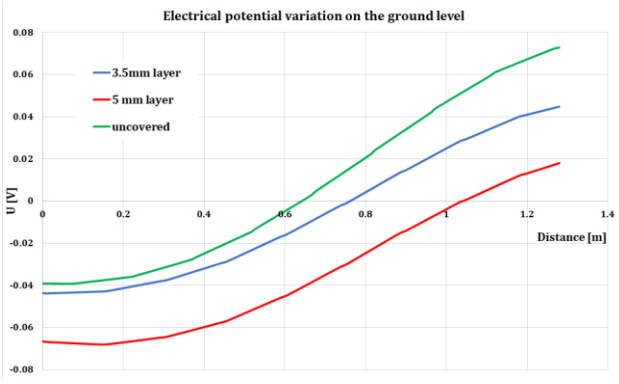


Figure 9. Comparison between the electrical potentials at the ground level.

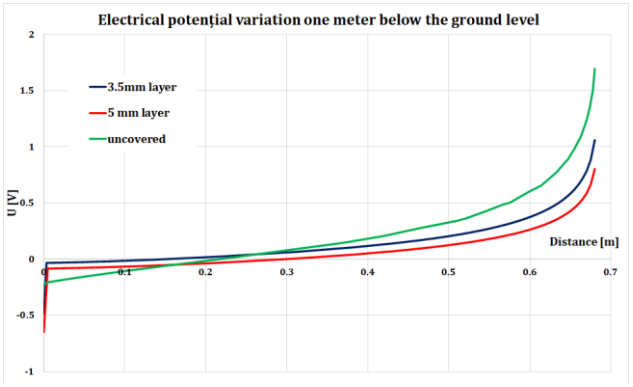


Figure 10. Comparison between the electrical potentials one meter below the ground level.

The study also followed the analysis of the density of the electric conduction current between the pipeline (acting as a cathode) and the protection electrode (acting as an anode). Thus, Figures 11 and 12 illustrate the spectrum of this current density (module) for the uncovered case, and for pipeline covered with 5 mm, respectively.

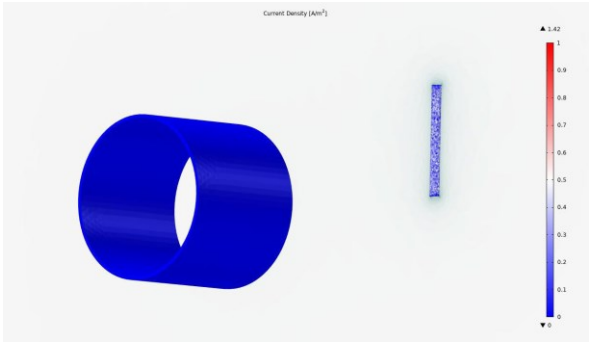


Figure 11. Electrical current density for uncovered pipeline.

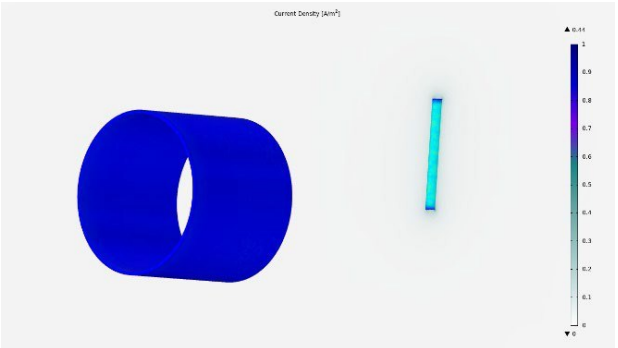


Figure 12. The electrical current density for a 5 mm protective layer.

Also, in Figure 13 it can be depicted a comparison between the density of the electrical current for the three studied situations (one meter below the ground level).

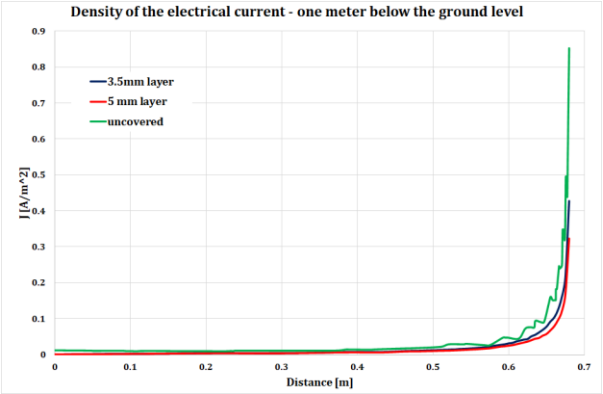


Figure 13. Comparison between the densities of the electrical current one meter below the ground level.

4. INFLUENCE OF THE ELECTRODE PLACEMENT

The second aspect studied in this paper was the influence of the distance between the protective electrode and the pipe. Thus, it started from 0.4 m between the electrode and the pipeline, moving the electrode 0.2 m apart by up to one meter. Figures 14 and 15 show the electric potential spectra for extreme cases. Figure 16 shows a comparison between the values obtained at ground level.

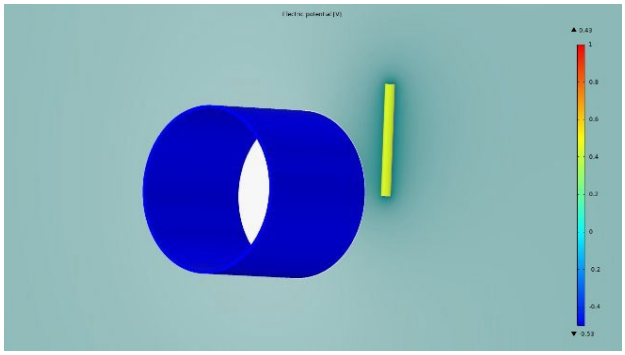


Figure 14. Electrical potential for 0.4 m between the pipeline and the electrode.

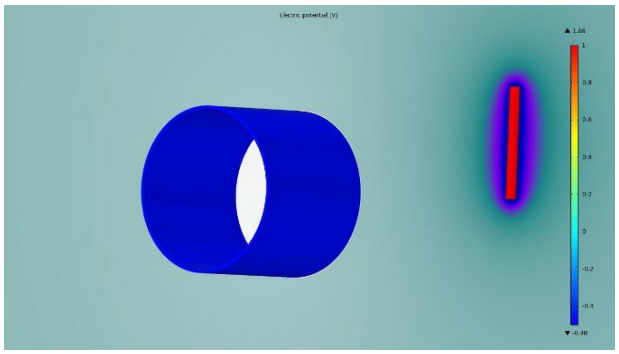


Figure 15. Electrical potential for 1.0 m between the pipeline and the electrode.

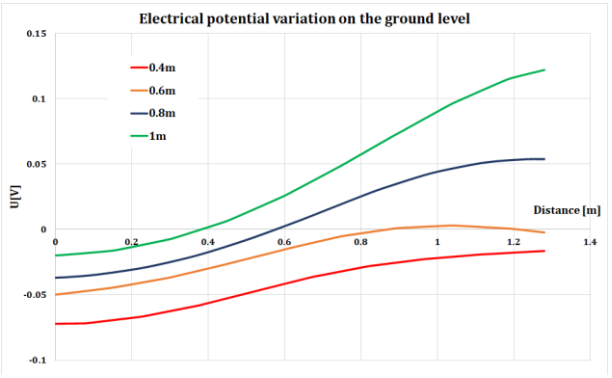


Figure 16. Comparison between the electrical current densities one meter below the ground level.

From the point of view of the placement of the electrode in front of the pipe, it is found that the reduction of the potential is achieved at about 0.4-0.6 m. However, the technical aspects of the placement of the cathodic protection system may be more practical than the result of these simulations and may impose the distance between the two subassemblies.

5. INFLUENCE OF THE SOIL CONDUCTIVITY

The electrical conductivity of the soil is a particularly important aspect in the study of the corrosion of buried pipelines. The range of variation of this parameter is very wide [13, 22, 23] starting from 0.2 - 2 mS/m for sandy, loose soil, 3 - 20 mS/m for normal soil, reaching 10-1000 mS/m for clay soil (depending on its humidity).

However, in environment linear models we find a direct proportionality between the values of the electric potential and the conductivity, so an increase in conductivity will simply lead to a proportional increase in the electric potential. In this study we looked at the influence of soil conductivity variation by simulating cases in which the pipeline and the electrode are placed in soils with different properties. This is possible when digging for the electrode into the ground and locally modifying its properties.

For this study, one chose three types of soils having: σ = 0.001 S/m – sand, σ = 0.01 mS/m - mud and σ = 0.1 mS/m - slag. In geometry, a cylindrical region with a radius of 0.2 m around the electrode has been defined, which will be characterized by the electrical conductivity σe, and the rest of the medium is characterized by the conductivity σs.

In the following images one can view the electrical potential spectrum for some of the studies cases (Figures 17 and 18) and the density of the module for the electrical current spectrum (Figures 19 and 20), respectively.

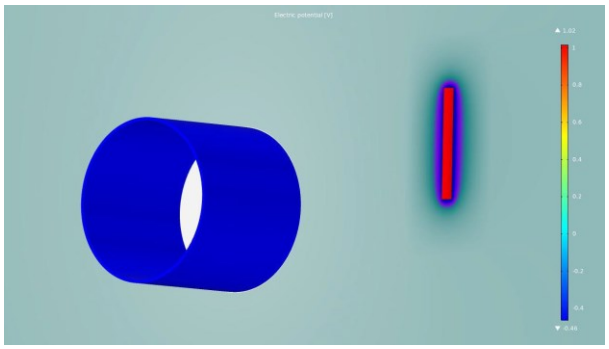


Figure 17. Electrical potential for σe = 0.001 S/m and σs=0.01 S/m.

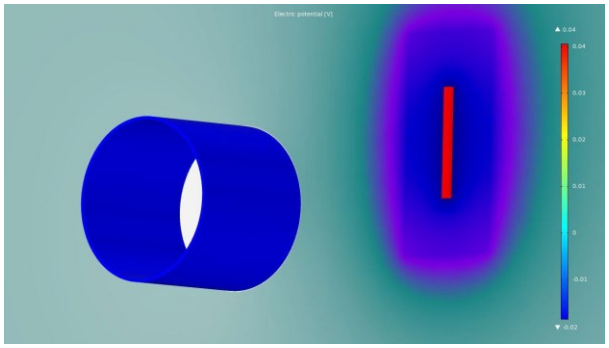


Figure 18. Electrical potential for σe = 0.1 S/m and σs=0.01 S/m.

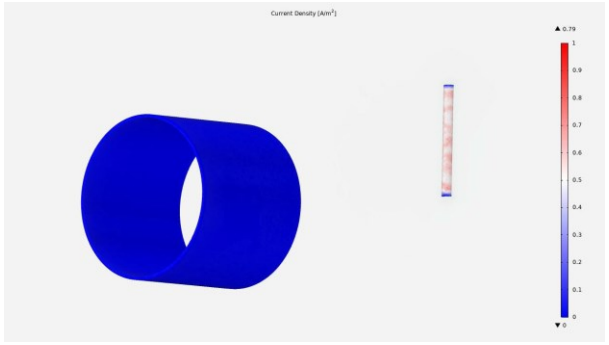


Figure 19. The electrical current density for σe = 0.001 S/m and σs=0.01 S/m.

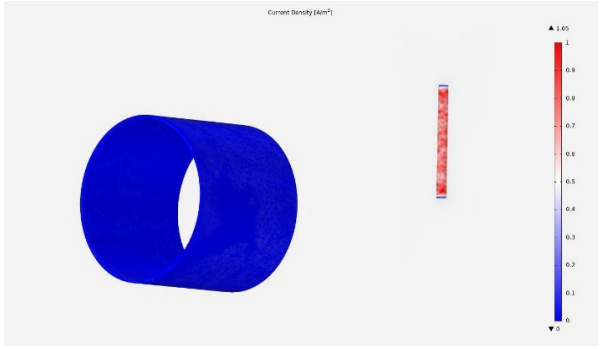


Figure 20. The electrical current density for σe = 0.1 S/m and σs=0.01 S/m.

The last three images are dedicated to presenting the comparisons of the values of the electric potential at ground level (Figure 21), of the electric potential at the pipeline-electrode level (one meter below ground level – Figure 22), and for the density of the electric conduction current between the pipe and the electrode (Figure 23), respectively.

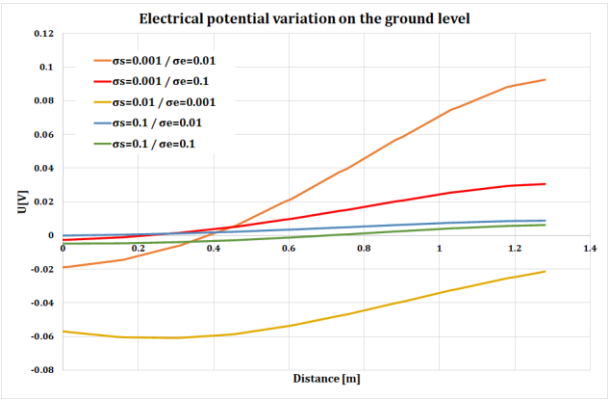


Figure 21. Comparison between the electrical potentials (ground level) for different combination of conductivity.

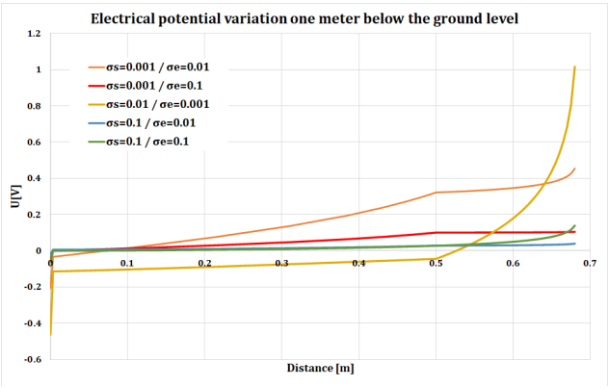


Figure 22. Comparison between the electrical potentials (one meter below the ground level) for different combination of conductivity

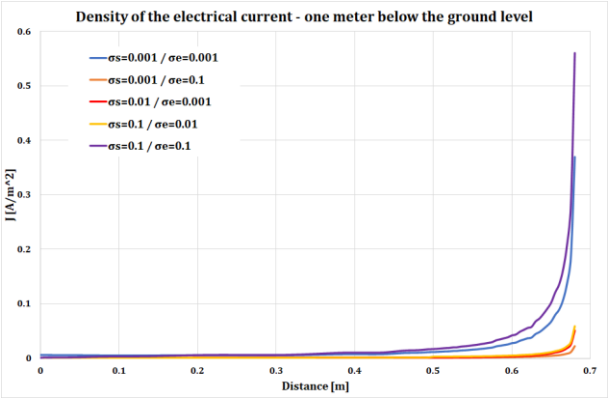


Figure 23. Comparison between the densities of the electrical current for different combination of conductivity.

The combinations of the conductivity of the two soil regions considered indicate quite significant variations. From the point of view of the electric potential, the most unfavorable situations are those in which the studied regions are characterized by a combination between a sandy soil and a muddy one.

In terms of current density, the highest values are recorded when the conductivity is the same in both regions.

6. CONCLUSIONS

Corrosion of underground pipelines is the main cause of maintenance costs, and the achievement of effective cathodic protection can lead to a reduction in these costs. This paper deals with several aspects of modeling a cathodic protection system using modern 3D simulation techniques.

Using real data on the geometric dimensions, as well as the properties of the materials involved (pipeline, insulating layer, soil) a study was performed varying several parameters to optimize the cathodic protection system.

The electrode is considered to have a fixed current density, but this information is strictly necessary for choosing the type of electrode. In addition to a maximum permissible current, the electrode is also characterized by a period of operation, an important aspect in its selection.

The first part of the paper clearly highlights the advantages of covering the pipeline with a 3.5 mm or 5 mm HDPE layer. Thus, the electric potential between the pipeline and the electrode decreases significantly both at ground level (Figure 9) and one meter below it (Figure 10).

The second aspect studied was the placement of the electrode near the buried pipeline. Thus, it can be seen (Figure 16) that placing it as close to the pipe as possible reduces the electrical potential at ground level. However, the limitations imposed by the system placement environment must also be considered.

The last part of the study looked at the differences that may occur in terms of electric potential, respectively the density of the electric current if the environment in which the cathodic protection system is placed is characterized by soils with different electrical properties (different conductivities). In this sense, a series of situations were simulated in which the freshly buried electrode benefits from a different soil than the nearby pipeline. Comparative results on various configurations can be seen in Figures 21, 22 and 23.

The results of this study can be used at the design stage of such a system by reducing several iterations on several parameters.

7. ACKNOWLEDGEMENTS

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