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BEM simulation on the influence of dispersion currents on buried pipes

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Abstract: The aim of this paper is to provide a method for modelling the influence of stray currents on buried pipes, using as calculation the boundary element method (BEM), using the module dedicated to corrosion in COMSOL Multiphysics software, which allows investigation both macroscopically and microscopically of corrosion processes. Dispersion currents, often called stray currents, are considered currents that follow little-known trajectories in the ground, but which can affect underground gas pipelines. Their sources are external to the pipes and contribute to the lowering of the anodic potential up to values to which the accelerated anodic dissolution of the metal occurs. For the simulation, the geometric modelling of a soil cube was used, in which pipes of different sizes are inserted, protected or not by a polyethylene protection state, in different positions and different burial depths. Using a calculation algorithm that is based on the boundary element method, the dynamics of the cathodic protection for the buried gas pipes in the presence of stray currents can be modelled.

Keywords: stray currents, corrosion, pipe potential, ground resistivity, polarization.

1. Introduction

Corrosion in the presence of stray currents occurs whenever the current in the ground leaves the pipe, here the character of the metal being anodic. This type of corrosion is specific to pipes in the vicinity of medium and high voltage power lines, electrified railways and tram lines, galvanizing coatings, DC welding workshops, poorly insulated underground electrical installations, of cathodic protection systems with current injection, of its communication antennas and other [1, 2].

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pipelines. Their sources are external to the pipes and contribute to the lowering of the anodic potential up to values to which the accelerated anodic dissolution of the metal occurs.

Sources of leakage currents can be natural or artificial, depending on the source that produces them. Natural sources are electrical atmospheric discharges that touch the earth and earth currents. In this case, the location on the ground of the lightning impact is random, but its effect can be felt at important distances if the metal, aerial or underground pipes participate in the movement of the current. Earth currents are the result of the activity of the earth's magnetic field and are manifested over very long pipe lengths.

Artificial sources originate from activities that lead to current losses in the ground or directly by induction in the transmission pipes. These sources are direct current or alternating current.

DC leakage currents are a risk factor for the integrity of underground metal pipes.

The direct current sources, which use the earth for returning to the source, directly affect the buried metal pipes and installations. Ground current is generally variable in intensity, direction, travelled route and time. The lower the soil resistivity, the higher the corrosion rate [1, 2]. Direct return current also affects earthing installations because they are electrically connected to each other or to the pipes they protect. In the case of overhead power lines, the current returning through the ground represents up to 50% of the traction current [3].

In the absence of cathodic protection, the current input constitutes the cathodic zone, and when leaving the pipe, the zone becomes anodic, where the strong degradation by electrolysis is manifested [2]. If the underground metal pipe is cathodically protected, the leakage current is added to the protection current, the risk of corrosion depending on the level of polarization of the pipe.

In the case of overhead power lines [4], the magnitude of the voltage induced in the pipe depends on the distance between the phases of the power line, the distance between the power line and the underground or overhead pipe, the length of the pipe exposed to the influence of the power line.

In the case of metal pipes, the intensity of corrosion caused by dispersion currents depends on the following factors:

- current density induced in the pipe;
- the values of the ON and OFF potentials of the pipe;
- dimensions of insulation defects;
- chemical composition and local resistivity of the soil;
- the possibility of salts forming on the pipe surface as a result of cathodic reactions

Stray currents flow through soil or concrete, but also through other conductive media such as water or snow, through disused metal pipes, etc. Usually, the dispersion currents fluctuate in intensity and direction and accelerate corrosion.

Depending on the direction of the dispersion currents, which change the potential of a metal pipe in relation to the environment, the influence can be favorable or unfavorable. In the absence of cathodic protection, the place of current entry into the underground pipe is the cathodic area, and the area where the pipe leaves becomes anodic, where a degradation by electrolysis is manifested. If the underground metal pipe is cathodically protected, the leakage currents are added algebraically to the protection current and in this case the risk of corrosion depends on the level of polarization acquired by the pipe.

Checking the presence of stray currents acting on the underground pipe is done periodically, because the local conditions can change over time. The periodicity of the control cannot be longer than 1 year. In order to avoid destruction, but also mutual influence, the regulations in force impose strict conditions on the approach, parallelism and intersection of OHL by pipelines. It is desirable that these situations be avoided as much as possible. De dorit este ca aceste situații să fie evitate pe cât posibil. The standard SR EN 12954: 2002 [5], as well as EN 50162: 2004 [6] specifies that in the case of the long-term influence of an alternating electric current on the metal pipe, it is necessary to consider the possibility of corrosion in alternating current.

In general, the current induced in the pipe depends on the voltage of the nearby power line and the configuration of the phase conductors and the neutral conductor, the distance between the lowest cable to the pipe, the insulation resistance of the pipe and the resistivity of the ground above the pipe. The presence of leakage currents in underground pipes with good insulation is felt over a longer length than those with aged insulation.

Corrosion of buried natural gas pipelines caused by leakage currents is a technical industrial and environmental problem. The study of dispersion currents and their influence on buried natural gas transmission pipelines will improve the methods of protection against corrosion and help to better understand the complex physical and chemical phenomena that are involved in the corrosion process. Because pipe corrosion is a destructive process and material losses caused by corrosion are very high, including not only metal consumption but also its effects on the operational safety of corrosion-affected installations, the introduction of a lifetime prediction program will increase safety in operation of buried pipes and will decrease the level of investments for their repair and maintenance.

Because measuring the potential of the pipeline is one of the methods to identify the presence of dispersion currents and their intensity, COMSOL Multiphysics software will be used to model the dynamics of the buried pipeline [7]. This software offers a simple and accurate method for modelling the problems caused by corrosion which in its turn was caused by the presence of dispersion currents, by introducing a corrosion module that allows the investigation of both macroscopic and microscopic corrosion processes. Tafel, Butler-Volmer equations or predefined equations can be used to model the potential and distribution currents in the corrosion process but also the kinetics of electrochemical reactions. Numerical methods that can be applied in corrosion simulations include the finite difference method, the finite element method and the boundary element method. The boundary element method has the advantage of being able to be applied to systems that include an infinite range and predefined boundaries of interest that we focus on in the study. Using a calculation algorithm that is based on the boundary element method, the dynamics of the cathodic protection for the buried gas pipes in the presence of stray currents can be modelled.

2. Numerical simulation

The numerical simulation involves the use of COMSOL Multiphysics 5.4 [7] and involves the study of an earth cube, measuring 50 x 50 x 50 m (figure 2), in which pipes of different sizes are inserted, protected or not by a state of polyethylene protection, in different positions and different burial depths. One of the pipes will be protected by an SPC and the effect of leakage currents on the unprotected pipes will be studied. Therefore, the following will be taken into account: pipe diameter, pipe wall thickness, construction material, resistance of the pipe protection layer, anode location to study the effect of stray currents on the change of crossing angle, intersection distance, distance between pipes, soil resistivity, anode output current, burial depth, soil resistivity influence. The polarization of the anode surface is ignored. The polarization curve of the X80 steel was measured using a conventional three-electrode cell assembly. The polarization curve obtained from experimental measurements against a Cu/$CuSO_4$ reference electrode is used at the cathode limit condition and due to the fact that it is not a linear curve, an interpolation function is introduced depending on the current density (fig. 1).

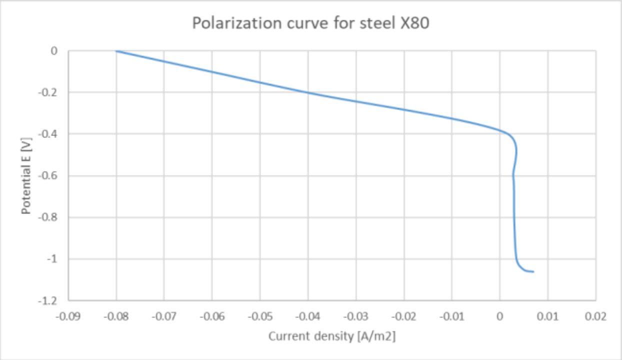


Fig. 1. Polarization curve

In the simulation performed, the protected pipe acts like a cathode, while the unprotected pipe corrodes in the soil, where anodic and cathodic reactions take place simultaneously. The initial value of the electrolyte was set at -0.9 V, compared to the reference electrode Cu/$CuSO_4$.

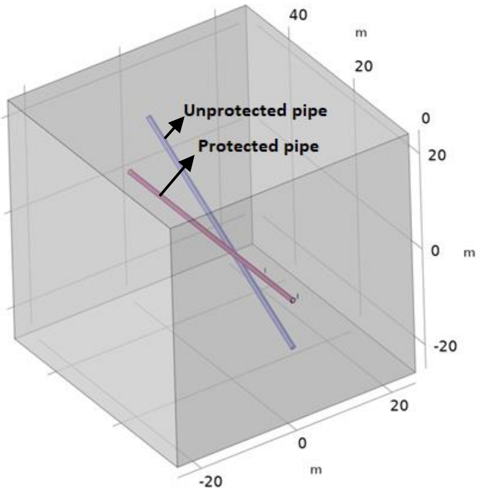


Fig. 2. Simulated stand geometry

In order to be able to model the process, several hypotheses will be accepted: the soil is uniform and electrically neutral, there is no concentration gradient in the soil / electrolyte, the soil is an electrolyte that carries the electric charge under normal ohmic resistivity conditions. Under these conditions the Laplace equations describe the equilibrium of the electrolyte potential [7]:

$$\nabla \bullet (i) = 0 \quad i = -\sigma \nabla \varphi, \tag{1}$$

where i is the current density [A/m^2]; σ is the electrical conductivity of the soil [S/m];

φ – is the potential [V]. For soils with a constant conductivity, the equations are reduced to:

$$\nabla^2 \varphi = 0, \tag{2}$$

Laplace equation that can be solved by applying boundary conditions [7]:

$$\varphi = \varphi_0,\ i = i_0,\ i_a = f_a(\varphi_a),\ i_c = f_c(\varphi_c), \tag{3}$$

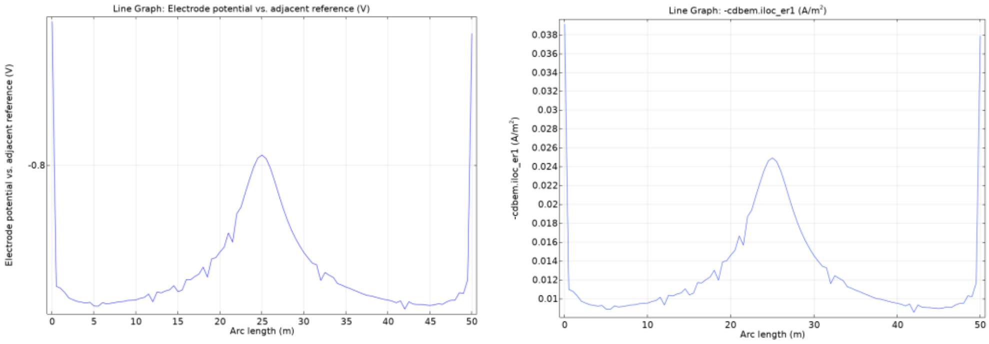
where φ_0 and i_0 are constant values of the potential and current density, and $f_a(\varphi_a)$, $f_c(\varphi_c)$ are interpolation functions that describe the kinetics of the anodic and cathodic electrode.

In order to be able to solve the differential equations and to be able to integrate them, in order to then be discretized, contour elements defined in the application are used in the simulation. The integral equations of the boundary elements are reduced to a system of linear equations, which depends on the geometric model and the number of nodes, which is influenced by the level of granularity defined by the discretization step which is directly related to the level of detail of the 3d canvas (mash) describing the geometric pattern. Following the automatic solving in COMSOL of the chosen geometric model resulted for a discretization step of 0.008193, a number of edge elements equal to 1878, a number of limit elements equal to 9792 and a total number of elements equal to 99 594.

3. Interpretation of results

3.1. The effect of pipe intersection

To study the effect produced by the intersection of pipes, consider two pipes spaced from each other at 2 meters. The pipe protected by current injection has an outer protective layer characterized by 500 ohms/m^2.



a. Distribution of potential

b. Distribution of dispersion currents

Fig. 3. Intersecting pipes: potential variations and current densities

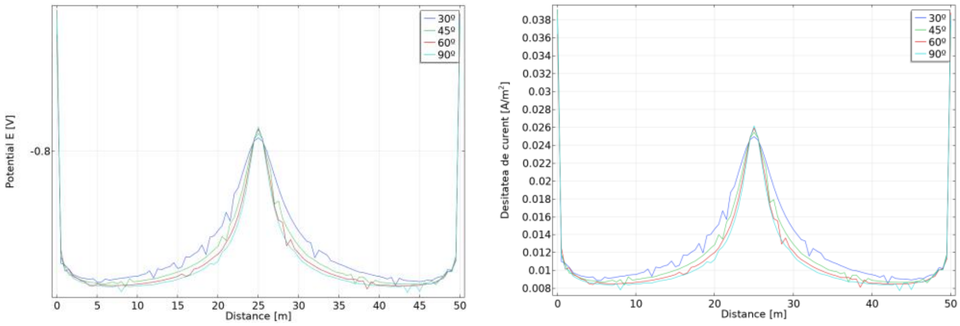
The simulation result is obtained in figure 3, where the potential distribution and current density in the electrolyte and pipes are observed depending on the distance of the dispersion current source. The ground resistivity is set to 500 ohm*m (Ω·m), the ground conductivity is 0.005 S / m, the intersection angle is 30 degrees. It is observed that at the point of intersection the distribution of potential and the distribution of current density have a maximum, and then decrease as we move away from the point of intersection.

From this we deduce that the point of intersection is the most affected in terms of corrosion, while the ends of the pipe are the least affected.

3.2. The effect of the intersection angle

In the simulation, the following angles were taken into account: 30^o, 45^o, 60^o and 90^o rotating in the unprotected pipe around the one protected by cathodic protection with current injection. The other parameters remained unchanged.

After obtaining the results from the simulation, it can be concluded that near the intersection point the potential becomes more negative with the decrease of the angle from 90^o to 30^o, the variation of the potential being about 1 [mV] si a densității de curent de 0.02 [A/m^2]. It is concluded that the shape of the graph of the potential variation is similar to the shape of the graph (fig. 4) of the variation of the current density.

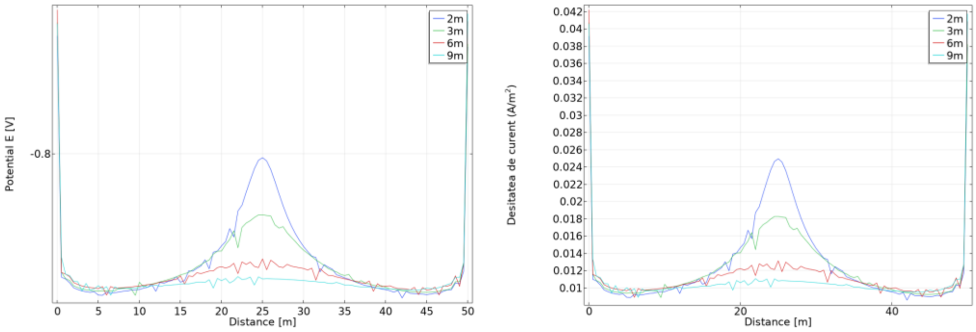


a. Distribution of potential b. Distribution of current density

Fig. 4. The effect of the intersection angle

3.3. The effect of the intersection distance

In order to highlight the effect of the distance at which the pipes intersect, the simulation was performed by positioning the pipes at the intersection point at distances of 2 m, 3 m, 6 m and 9 m, keeping the rest of the parameters unchanged. The obtained results are presented in figure 5.



a. Distribution of potential b. Distribution of current density

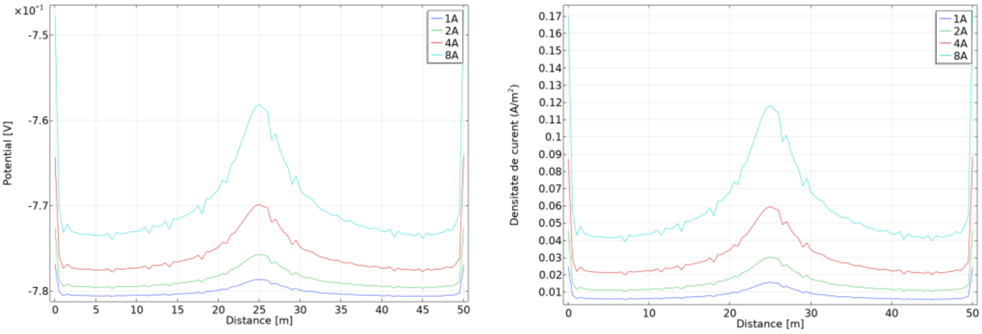
Fig. 5. The effect of the intersection distance

Figure 5.a shows the variation of the potential distribution through the cross section that includes the projection of the point of intersection between the two pipes, depending on the distances chosen as mentioned above. Figure 5.b highlights the current density distribution through the cross section made by projecting the point of intersection of the two pipes, depending on different distances at which the two pipes are placed.

After obtaining the result from the simulations, it can be concluded that the spacing of the pipes at the intersection point has the effect of decreasing the potential and the current density, directly proportional to the distance between the pipes. It is also observed that the appearance of the graphs is similar.

3.4. The effect of the anode output current

For steel pipes, the polarized potential range measured from the Cu/$CuSO_4$ reference electrode is -0.85 V to -1.2 V, according to [Romanian standard 7335/6 and NACE SP0169. The simulation will be performed to calculate the potential distribution and current density distribution along the unprotected pipe. All other parameters remain unchanged. From the simulation it is observed how the output current from the anode has as effect the displacement of the potential distribution towards the less electronegative part, and the effect of the current density is similar but with a displacement towards the positive part. Therefore, it can be concluded that the increase of the output current from the anode has as effect an increase of the dispersion currents and implicitly of the current density on the surface of the unprotected pipe, which will have the effect of a faster corrosion of the pipe in the intersection area. The simulation results are presented in figure 6.



a. Distribution of potential

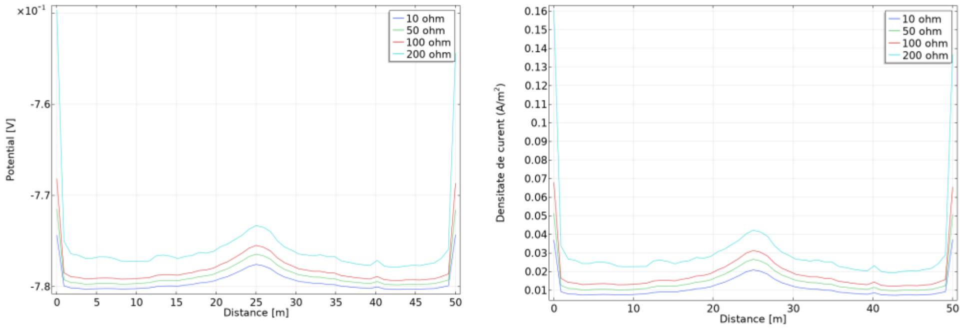
b. Distribution of current density

Fig. 6. The effect of anode output current

3.5. The effect of changing soil resistivity

The simulation will be done at different ground resistivities: 10 Ωm, 50 Ωm, 100 Ωm and 200 Ωm, in order to obtain the values of the potential distribution and the current density distribution. Other parameters remain unchanged.

The results indicate an increase in potential distribution and current distribution with decreasing soil resistivity. From this we deduce that for soils with low resistivity the corrosion is more aggressive on the pipe which is free. The simulation results are presented in figure 7.

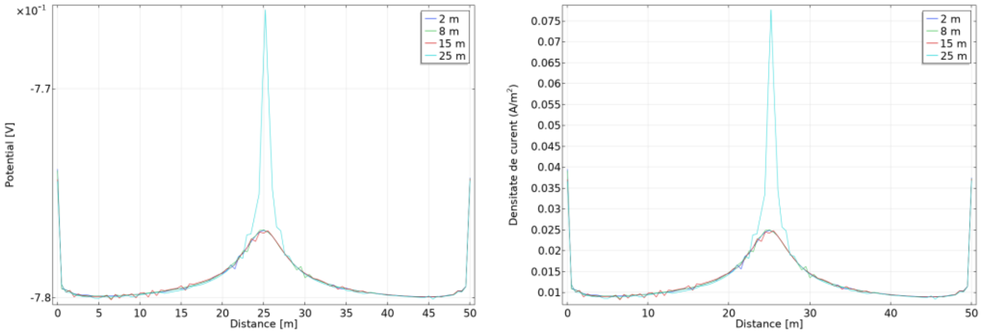


a. Distribution of potential b. Distribution of current density

Fig. 7. The effect of anode output current

3.6. The effect of the position of the anode

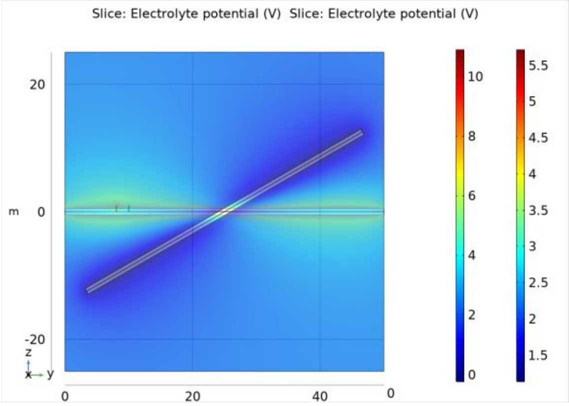
The simulation is performed for a soil of medium aggressiveness, with a resistivity of 50 Ωm. The position chosen for the anode is for moving the anode on the y axis, at the following locations along the protected pipe: 2 m, 8 m, 15 m and 25 m. The 25 m location coincides even with the intersection of the pipes. The result of the simulation is presented in figure 8.



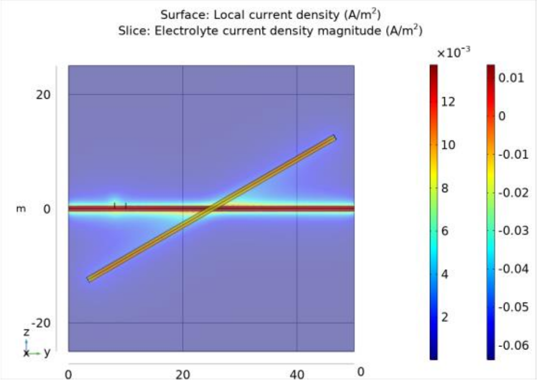
a. Distribution of potential b. Distribution of current density

Fig. 8. The effect of the anode output current

The simulation result indicates that both the potential distribution and the current density distribution of the free pipe remain almost unchanged when we change the position of the anode, except for the proximity to the intersection point. At the point of intersection the effect is maximum, so the pipe will corrode the most at the point of intersection. The current produced by the anode changes the potential and current density of the protected pipe, producing leakage currents that migrate to the unprotected pipe. The effect of these currents is maximum at the point of intersection. It can also be seen in Figure 9.a. the effect of changing the potential distribution in the soil, and in figure 9.b. the effect produced by the anode on the current density in both the protected and the unprotected pipe.



a. Distribution of potential in soil, anode located at 8m



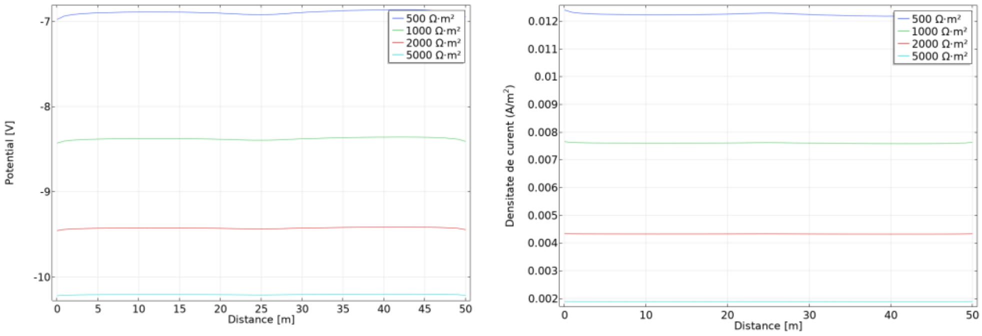
b. Current density distribution, anode located at 8m

Fig. 9. The effect of anode output current

3.7. The effect produced by the resistivity of the insulation

The simulation was performed by changing the surface resistance of the insulation layer of the unprotected pipe, which is under the influence of dispersion currents, at values of: 500, 1000, 2000 and 5000 $\Omega\cdot m^2$ and maintaining a surface resistance of the insulation of 500 $\Omega\cdot m^2$ for the pipe protected by current injection. The next step in the simulation was to change the surface resistance of the insulation layer for the pipe protected by current injection at values of: 500, 1000, 2000 and 5000 $\Omega\cdot m^2$, keeping the pipe free unprotected by a layer of insulation. The result of the simulation is presented in figure 10. In both cases, the other parameters chosen in the simulation remained unchanged.

The result indicates that both the potential distribution and the current density distribution change with the resistivity of the pipe insulation. When the resistivity of the insulation protection layer is very high, the pipe is protected and the current density is very low.

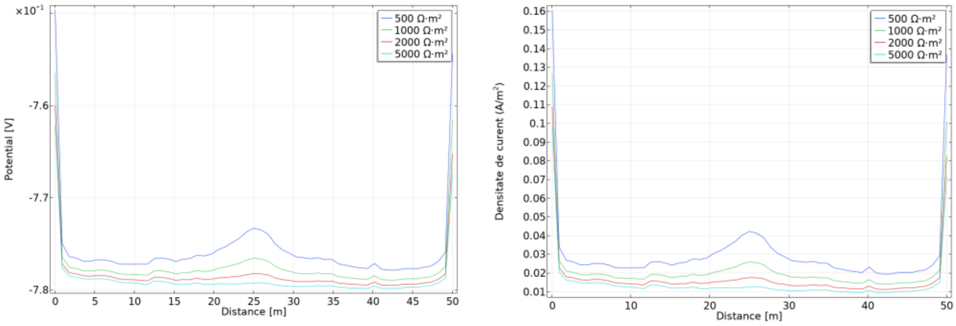


a. Potential distribution, cathodic unprotected pipe

b. Current density distribution, free pipe

Fig 10. The effect of anode output current

For the unprotected pipe by current injection, changing the type of insulation, works as a protective screen against leakage currents, having an effect of reducing the potential distribution directly proportional to the resistivity of the insulation. The same observation is for the distribution of the current density of the pipe.



a. Potential distribution, protected pipe

b. Current density distribution, protected pipe

Fig. 11. The effect of anode output current

Changing the resistance of the pipe insulation has the effect of shifting the potential and current density of the pipe to minimum values depending on the value of the resistivity from maximum to minimum (figure 11 a, b). A similar effect can be observed in the case of changing the insulation resistance of the pipe protected by current injection. At the same time, the point of intersection is the area where the effect of corrosion will be most evident.

4. Conclusions

The causes of damage to gas transmission pipelines are outlined in the analysis of factors that must be considered according to the potential hazards specified by the ASME B31.8S standard, which recommends the division into three types of factors that can cause the failure of pipelines for each type consisting in three categories of dependent, stable and time-independent factors, each category being organized by types of factors, resulting in a total of 21 types of factors. Analyzing these factors, we can conclude the following causes of damage to gas transmission pipes, depending on their weight: external corrosion, cracked corrosion under stress, third party interventions, incorrect operation, manufacturing defects of pipes and welded joints of pipes, construction or assembly defects - welding, equipment defects, internal corrosion and external or weather-related forces. However, the main cause affecting the integrity of natural gas transmission pipelines is corrosion. The soil in which these pipes are buried is an open system and plays a decisive role over time in the corrosion process through the permanent exchange of matter and energy with the atmosphere, biosphere and hydrosphere. Among the physical properties of the soil are mainly those that determine the permeability of the soil to gas and water, resistivity and corrosion process, all being dependent on the characteristics of the three constituent phases of the soil: liquid, solid and gaseous. Collaborated with the phenomenon of electroosmosis that takes place at the manometric scale, under the action of an external electric field, at the interface of the soil particle-interstitial solution, the corrosion phenomenon is accelerated by the forced penetration of water into the pores of passive protection materials. -and electrical insulation characteristics much faster. At the same time, by migrating the water to the cathode, the resistivity around the pipe is reduced and the aggressiveness of the soil increases [8].

Corrosion protection by duplex protection (passive and active) requires a correct application, but also a permanent control because in addition to the beneficial effects the cathodic protection modifies, in the sense of worsening the properties of the materials that make up the passive protection systems. Under the conditions of applying cathodic protection, at parameters that exceed the limits of the optimal field of application, (-1200 mV la -850 mV), the aging process of the insulation can be accentuated by the phenomenon of electroosmosis, a phenomenon that consists in the penetration of water under the action of potential difference on the thickness of the insulation.In this sense, the penetration by diffusion to the metal of the corrosive agents and the existence of the defects that cross the insulating layer are important.

The simulations performed in this article are an attempt to approximate and model the physical and chemical processes that affect natural gas transmission pipelines in the presence of stray currents. The evaluation of the influence of stray currents on the passive protection but also on the metallic material of the buried gas transmission pipes imposes a need to predict when to intervene to correct, before the occurrence of undesirable events on the operational safety of corrosion-affected installations, which require repairs and replacements.

The simulations highlight the influence of active protection on the pipes that are in the immediate vicinity of the cathodically protected pipe. Thus, it could be highlighted how in the intersection point, although the pipes are spaced from each other, the potential distribution and the current density distribution has a maximum.

With the distance from the intersection point these values decrease to approximately zero values. It was also observed how the potential distribution and the current density distribution are influenced by the intersection angle of the two pipes and the distance between the two pipes. Near the intersection point the potential becomes more negative as the angle decreases from 90 ° to 30 ° and how the distance of the pipes at the intersection point has the effect of decreasing the potential and current density, directly proportional to the distance between the pipes.

The simulation of the effect of the output current from the anode allowed the modelling of the influence that this current has on the dispersion currents that are formed and implicitly on the current density on the surface of the unprotected pipe. The effect of changing soil resistivity indicates that in soils with low resistivity, corrosion is more aggressive, and soils with high resistivity have a corrosion-reducing effect. At the same time, it could be highlighted how the change of the anode position does not influence the potential distribution as well as the current density distribution of the unprotected pipe. Thus, it was possible to highlight the presence of dispersion currents that form and migrate to the unprotected pipe.

Modelling the effect produced by the resistivity of the insulation layer allowed highlighting its influence on the potential distribution as well as the current density distribution for the unprotected pipe. Thus the resistivity of the insulation protection layer is very high, the pipe is protected and the current density is very low.

All these simulations were performed to find a law that would allow finding a maintenance program for pipelines that would allow an optimization of the lifespan of buried natural gas transmission pipelines. Therefore, predicting the influence of stray current sources on the values of induced currents in the pipe is important in order to protect these pipes, because pipe corrosion is a destructive process and material losses caused by corrosion are very high, including not only metal consumption but also its effects on the operational safety of installations affected by corrosion. The introduction of a program to predict the service life will increase the operational safety of buried pipes and will reduce the level of investment for their repair and maintenance.

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