Numerical Simulations of Factors Affecting Stray Current Corrosion on Pipeline

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Abstract. Stray current can cause severe corrosion on buried steel pipelines. To investigate the corrosion effect of stray current, originating from impressed current cathode protection system of pipeline, on interference pipeline, a numerical model based on boundary elements using commercial software COMSOL Multiphysics was developed to simulate corrosion potential and stray current density distribution on interference pipeline. The model geometry was comprised of the cathodically protected pipeline, interference pipeline and an auxiliary anode. The effects of crossing angle and crossing distance of the two pipelines, output current and location of anode, soil resistivity and coating surface resistivity were investigated. The results demonstrated that the impressed current cathode protection system substantially affects the corrosion potential and current density distribution of interference pipelines in vicinity of crossing. The crossing angle and vertical distance of two pipelines have no important influence while the anode output current, anode location, soil resistivity and coating surface resistivity have significant influence to stray current corrosion on interference pipeline.

1. Introduction
The buried pipeline external corrosion protection techniques that are used most often are cathodic protection (CP) and protective coating [QIU (2003)]. Chemical degradation of pipeline steels at coating failure sites is lessened by CP systems [Gadala (2016)], but the pipelines which are present within the current flow of the impressed current CP (ICCP) system may suffer the direct current stray current corrosion originating from ICCP leading [CAO (2010); ZHAO (2016)]. With the development of electrochemical theory and computer technology, numerical simulation methods have been proved to be powerful tools to investigate the effectiveness of CP system and stray current corrosion on pipelines [KOU (2017); LIU (2015); Gan (2016)]. With the development of electrochemical theory and computer technology, numerical simulation methods have been proved to be powerful tools to investigate the effectiveness of CP system and stray current corrosion on pipelines [KOU (2017); LIU (2015); Gan (2016)]. Numerical methods applied to corrosion studies have included the finite-difference method (FDM), the finite-element method (FEM) and the boundary element method (BEM) [IMetwally (2007)]. The BEM has the distinct advantage over the other two methods to apply to systems that include an infinite domain and the domain whose boundary only is required to be discrete, such as cathodic protection of pipelines and offshore structures [IMetwally (2007); Abootalebi (2010)]. The BEM needs fewer equations and a smaller matrix size than FEM and can solve both finite and infinite domain problems [Jia (2004)].

Li et al. [Li (2013)] deduced the mathematics model of the potential distribution by the tube element
method of boundary element algorithm. Using Matlab programming tools, the cathodic protection potential distribution of long distance pipeline was calculated and its comparison with that of the experimental designed pipeline showed similar results. Liu et al. [Liu (2011)] used numerical simulation calculation software BEasy to study the applied cathodic protection of platform. The results show that numerical simulation calculation can analyze the anode distribution and potential distribution on the surface of platform. Gan et al. [Gan (2016)] used the numerical simulation program BEASY to study the corrosion effect of DC stray current that an auxiliary anode bed generated in an impressed current cathodic protection system. The effects of crossing angle, crossing distance, distance of the two pipelines, anode output current, depth, and soil resistivity were investigated. In the study, the pipeline coating resistivity and anode location were not taken into account, so research results could be not conform with reality.

In this paper, a boundary elements model was developed to simulate electrode potential and stray current density distribution on interference pipeline (crossing with the ICCP Pipeline), to investigate the effects of crossing angle and vertical distance of the two pipelines, output current and location of anode, soil resistivity and coating resistivity on the stray current corrosion.

2. Numerical simulation

2.1 Governing equation and Boundary Conditions

Some assumptions are made here: the solution (soil) around the pipeline is uniform and electroneutral, and there is no concentration gradient in the solution. Since the soil is assumed to feature only charge transport with normal ohmic resistivity effects, the Laplace equation governs potential in the electrolyte [Bortels (2007)]:

$$\nabla \cdot (i) = 0 \quad i = - \sigma \nabla \varphi$$

where $i$ is the current density in mA/m$^2$; $\sigma$ is the electrical conductivity of soil in S/m; and $\varphi$ is the potential in V. For domains with a constant electrical conductivity $\sigma$, governing Equation (1) simplifies to:

$$\nabla^2 \varphi = 0$$

the Laplace equation is solved using the following boundary conditions [Abootalebi (2010)]:

$$\varphi = \varphi_0, \quad i = i_0, \quad i_d = f_d(\varphi_a), \quad i_c = f_c(\varphi_c)$$

where $\varphi_0$ and $i_0$ are given constant values of potential and current density, respectively. $f_d(\varphi_a)$ and $f_c(\varphi_c)$ are linear or non-linear functions that describe the anode and cathode electrode kinetics, respectively.

The boundary elements is to convert the partial differential equation to an integral equation, which is then discretized. The boundary integral equations for all elements can be assembled into system of linear simultaneous equations, which is expressed in a matrix form as follows [Bortels (2007)]:

$$H \varphi = G i$$

where $H$ and $G$ are problem influence matrices, respectively. The size of the system of equations is defined by the number of nodes. Partitioning the $\varphi$ and $I$ into those nodes which form the anode and the cathode regions, and the potential and current densities can be calculated using related equations.

2.2 Simulation with COMSOL

In this paper, the boundary element numerical simulation software COMSOL Multiphysics 4.3a was used. The simulation model was performed in accordance with Fig. 1 [Gan (2016)].
Figure 1. Model geometry comprises of anode, pipeline protected and interference pipeline which are surrounded by soil domain.

The model geometry is comprised of the protected pipeline, interference pipeline and anode, see figure 1. Both the protected and interference pipelines are 1.6 km long and cross each other at an angle of 90º and at middle of their lengths. The protected pipeline diameter is 0.813 m, the interference pipeline diameter is 0.406 m. The material of both pipelines are APL X80. The auxiliary anode which is vertically buried has the following parameters: two endpoint coordinates (-800 m, -200 m, -30 m) and (-800 m, -200 m, -50 m), diameter 0.2 m, constant current 1.6 A. Soil conductivity in the area of the buried pipelines is 0.02 S/m. The resistivity of coating on protected pipelines is assumed to 5000 Ω•m². The polarization on the surface of the anode was ignored. The polarization curve of steel X80 was measured in the soil environment using a conventional three-electrode cell assembly. The polarization curve is used as the cathode boundary condition, but it is a nonlinear curve, so we have to use polarization data in a piecewise linear interpolation approach, shown in Fig. 2. In order to purpose of this study, crossing angle and crossing distance of the two pipelines, output current and distance of anode, soil resistivity and coating resistivity take several different values during simulation and analysis. All simulated potential data below are with respect to the saturated copper sulfate reference electrode.

Figure 2. The polarization curve. a Experimental polarization curve. b Piecewise linear polarization curve
3. Results and discussion

3.1 Effect of pipeline crossing

Considering the situation of two pipelines intersecting, the setting of each parameter is the same as in Sect. 2. Both potential distribution and current density distribution of interference pipeline are obtained by simulation, and the results are shown in Fig. 3.

As shown in Fig. 3, the change in the potential and current density distribution of interference pipeline is very large where the two pipelines intersect. The corrosion potential near the intersection is higher than the self-corrosion potential $E_{\text{corr}}$, and the current density is more positive than self-corrosion current density $i_{\text{corr}}$. The potential at each end of the pipeline is lower than $E_{\text{corr}}$, and the current density at each end of the pipeline is negative. That means the section of the pipeline near crossing suffers corrosion more severe, while the each end of the pipeline receives some cathodic protection which reduces corrosion.

Figure 3. Effect of pipeline crossing. a Potential distribution. b Stray current density distribution

3.2 Effect of crossing angle

The four different angles of 30°, 45°, 60° and 90° are simulated by rotating interference pipeline anticlockwise, while all other parameters remain unchanged. As results of simulation, the both corrosion potential and current density distribution of interference pipeline are shown in Fig. 4.

Figure 4a reveals that the potential near the intersection becomes increasingly negative on decreasing the crossing angle from 90° to 30°. However, the change of potential is less than 10 mV. On the other hand, the calculated potential change at one end of the pipeline is relatively large. This is because the relative position between the pipeline and the auxiliary anode has changed more significantly while the location of both anode and intersection remains unchanged. The chance of current density is similar to potential, as shown in Fig. 4b.

Figure 4. Effect of different crossing angles. a Potential distribution. b Stray current distribution

3.3 Effect of crossing distance

The potential and current density distribution of interference pipeline buried at depths 1, 2, 3 and 8 m is simulated, while other parameters remain unchanged. The results are shown in Fig. 5.
The results indicate that both the pipeline corrosion potential and the current density only have small change at the point of crossing, the rest section are almost same completely. The change in depth of pipeline, in other words, vertical distance of two pipelines, is very limited, so the effects on interference pipeline is mild.

3.4 Effect of anode output current
The range of protection potential is generally -0.85 to -1.2V for steel pipeline regulated by related standard. We calculate the potential distribution and the current density distribution of interference pipeline for four anode output currents: 0.8, 1.2, 1.6 and 1.8 A, which can keep potential of protection potential within -0.85 to -1.2V. All other parameters remain unchanged. The results are shown in Fig. 6.

The anode output current has a strong influence on the magnitude of the stray current. Both the corrosion potential distribution and the current density distribution around interference pipeline change significantly with an increase in the anode output current. When the anode output current increases, at each end of the pipeline the potential is more negative and current flowing into pipeline is larger, but potential near the crossing is more positive and current flowing out pipeline is larger. That means the corrosion near the crossing is more serious.

3.5 Effect of anode location
The auxiliary anode can cause changing of soil nearby, so we change anode location to change distance between anode and pipelines. The potential and current density distribution of interference pipeline is simulated with anode X, Y coordinates (-0.2km, -200m), (-0.4km, -200m), (-800 m, -200m), (-1800 m, -200m), (-10.8 km, -200 m), while other parameters remain unchanged. The results are shown in Fig. 7.

The results indicate that both the potential and the current density of interference pipeline change significantly at the coordinates (-0.2km, -200m), (-0.4km, -200m), remain practically unchanged at
rest locations. The reason is that the electric field produced by anode current change the electrode potential, and change the current by electrode reaction.

![Figure 7](image1.png)

**Figure 7.** Effect of the anode location. a Potential distribution. b Stray current density distribution

### 3.6 Effect of soil resistivity

We simulate both the corrosion potential and the current density distribution for the pipeline with soil resistivity of 10, 50, 100, 200 and 500 Ωm. All other parameters remained unchanged. The results are shown in Fig. 8.

![Figure 8](image2.png)

**Figure 8.** Effect of the soil resistivity. a Potential distribution. b Stray current density distribution

The results indicate that both the potential and the current density of interference pipeline change significantly with different soil resistivities. When soil resistivity is small, the potential of interference pipeline is near to Ecorr and the current density is almost zero. With increasing of soil resistivity, the potential and the current density of interference pipeline become very uneven. The potential is more positive near the intersection, and more negative at the each end of the pipeline, while current density is also more positive near the intersection, and more negative at the each end of the pipeline. That means that the corrosion on pipelines is more severe when soil resistivity become larger.

### 3.7 Effect of coating resistivity

The ICCP can automatically adjust the magnitude of anode current to control the electrode potential of the protected pipeline within an adaptable arrange, such as from -0.85 to -1.25V. When the coating resistivity of protected pipeline is changed, the anode current will be changed accordingly to keep much the same electrode potential. The electrode potential of protected pipeline controlled at about -1.1V, the values of anode current calculated are 2.4, 1.5, 0.38, 0.2 and 0.04A respectively when surface resistivity of coating is assumed as 500, 1000, 5000, 10000 and 50000 Ω∙m², shown as Fig. 9. The potential and current density distribution of interference pipeline is simulated with above values for surface resistivity of coating and anode current. All other parameters remained unchanged. The results are shown in Fig. 10.
Figure 9. The electrode potential of protected pipeline with varied surface resistivity of coating and anode current

The results indicate that both the potential and the current density of interference pipeline change significantly with different surface resistivities of coating. When surface resistivity of coating is very large, the potential of interference pipeline is near to $E_{corr}$ and the current density is almost zero. With decreasing of surface resistivity, the potential and the current density of interference pipeline become very uneven. The potential is more positive near the intersection, and more negative at the each end of the pipeline, while current density is also more positive near the intersection, and more negative at the each end of the pipeline. That means that the corrosion on pipelines is more severe when surface resistivity of coating become smaller.

Figure 10. Effect of the surface resistivity of coating. a Potential distribution. b Stray current density distribution

4. Conclusions

The numerical simulation based on BEM is used to investigate factors affecting SCC on interference pipeline crossing the pipelines with ICCP. Numerical simulations based on BEM are a powerful aid to investigate potential and current density distribution of buried pipelines suffering SCC. Based on our simulation, the potential and current density distribution of the pipeline changes a lot when the pipeline is crossed by the pipelines with ICCP. The section of pipeline near the intersection has positive potential offset, and suffer the SCC, while each ends of pipeline far away from the intersection have a negative potential offset, and are protected by stray current.

The variation of the pipeline crossing angle and crossing distance has almost no influence on the potential and the current density distribution of the interference pipeline. That the location of anode is moved farther from pipelines hardly affect interference pipeline, but moving nearer to crossing, on the potential and the current density distribution of the interference pipeline are affected significantly. Upon increasing the anode output current, the soil resistivity, or decreasing surface resistivity of
coating, the electrode potential of the interference pipeline becomes very uneven, and the corrosion potential of the pipeline near the intersection has a larger positive offset that causes worse corrosion on pipeline.

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