Optimization of Cathodic Protection System Design for Pipe-Lines Structure with Ribbon Sacrificial Anode Using BEM and GA

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Abstract. In this paper, combination of a boundary element formulation and genetic algorithm (GA) is developed and used for analyzing of cathodic protection systems of buried pipe-lines structures. It is very important to maintain the effectiveness of the cathodic protection system for pipelines structure, in order to lengthen the lifetime of the system. However, nowadays the evaluation of the effectiveness of the system only could be done after the system applying in field. This study is conducted to combine 2D boundary element method (BEM) and GA in order to evaluate the effectiveness of the cathodic protection system for pipe-lines structure using ribbon sacrificial anode. Two factors i.e. the soil conductivity and the distance between pipe-lines and anode, are analyzed by using the proposed method. In this method, the potential in the domain was modeled by Laplace's equation. The anode and cathode areas were represented by polarization curves of different metals. Boundary element method was applied to solve the Laplace's equation to obtain any potential and current density in the whole surface of the pipe. The pipe and anode were modeled into 2D model. The numerical analysis result shows that the optimum distance between pipe-lines and anode can be determined by combining BEM and GA.

Introduction

Corrosion is a costly problem. According to the U.S. Federal Highway Administration (FHWA) released study, the total annual estimated direct cost of corrosion in the U.S. is $276 billion (about 3.1% of the nation's Gross Domestic Product (GDP) [1]. Also corrosion is a major cause of premature deteriorations and failures of the structures. Therefore, it is important to maintain a long life of the structures and reduce the cost of maintenances [2].

In many cases of corrosion, frequently due to economical reasons, the structures are protected by any protection system. One of the ways to reduce the corrosion cost is by implementing corrosion protection system such as cathodic protection. However, it is difficult to evaluate the effectiveness of cathodic protection system before the system applied. People only depend on the experience or trial-and-error. Hence, a method to evaluate the cathodic protection system before deployment becomes important.

The use of numerical method such as boundary element method (BEM) [3] becomes popular among researchers and corrosion engineer for modeling and solving various corrosion problems [4-7]. The mathematical model for the cathodic protection of tank bottoms using standard anode configuration was developed, which realistic polarization kinetics, non-uniform current distributions and non-uniform oxygen concentrations were taken account [8]. Some factors affecting cathodic protection interference was studied using BEASY software (BEM) in the reference [9]. Meanwhile, the optimum electrode position of cathodic protection sacrificial anode system for 2D steel storage tank was analyzed by developing BEM using MATLAB® in reference [10].

In this paper, the optimum displacement between pipe-lines and anode, and the influence of the soil conductivity to the potential distribution on the pipe surface that protected using cathodic protection with ribbon sacrificial anode (Fig. 1) are analyzed by applying combination the boundary element method (BEM) and genetic algorithm (GA)

General principles of cathodic protection

General principles of cathodic protection basically reduces the corrosion rate of a metallic structure by reducing its corrosion potential, bringing the galvanic potential of the metal to be protected to immune state level where anodic reactions are impossible for the given circumstances. The principle of cathodic protection is implemented by two ways that are sacrificial anode and impressed current.

Sacrificial anode systems use reactive metals as anodes that directly electrically connected to the metal to be protected. The natural potentials differences between the anode and the metal, as indicated by their relative positions in the galvanic series, generates a positive current to flow in the electrolyte, from the anode to the metal. Therefore, the whole surface of the metal becomes more negatively charged and becomes the cathode. The metals that commonly used as sacrificial anodes, are aluminum, zinc and magnesium.

The inert (zero or low dissolution) anodes is benefited by Impressed current systems. The systems use an external source of dc power (rectified ac) to impress a current from an external anode onto the cathode surface.

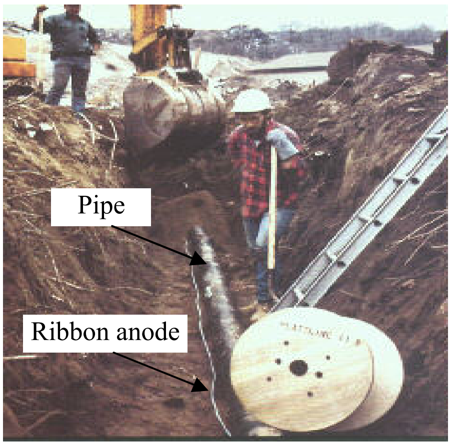

Figure 1. Cathodic protection system using ribbon sacrificial anode [11]

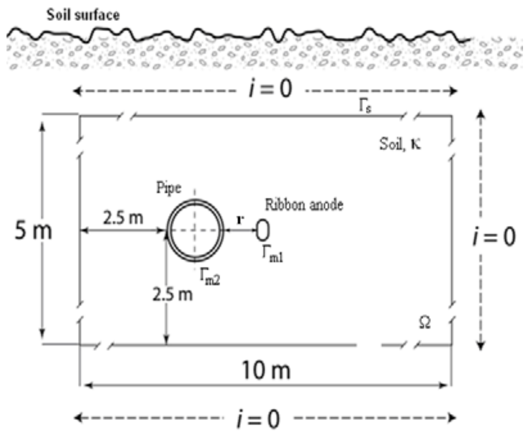

Figure 2. Cathodic protection with ribbon anode model in 2D

Modeling of Corrosion

For numerical analysis or simulation purposes, suppose that the soil domain (Ω) is (Γs) limited as shown in Fig. 2, the surface ribbon anode is (Γ_{m1}) and the surface of the pipe is (Γ_{m2}). The electrical conductivity (κ) is uniform in the whole soil domain and there is no accumulation or loss of ions in the bulk of the domain. Fig. 3 gives the boundary condition of the model.

The potential field in the soil domain (Ω) can be modeled mathematically by the Laplace's equation:

$$\nabla^2\phi = 0 \qquad \text{in } \Omega \tag{1}$$

The density of current (i) across the boundary is given by

$$i = -\kappa \frac{\partial \phi}{\partial \mathbf{n}} \tag{2}$$

where κ is the electrical conductivity and ∂/∂n is the outward normal derivative.

The associated boundary conditions to Eq. 1 are given as followings:

$$\mathbf{i = 0} \quad \text{on } \Gamma_s \tag{3}$$

$$-\phi_{\mathbf{a}} = f_a(i) \text{ on } \Gamma_{m1} \tag{4}$$

$$-\phi_{\mathbf{c}} = f_c(i) \text{ on } \Gamma_{m2} \tag{5}$$

where f_a(i) and $f_c(i)$ are the non-linear functions representing the experimentally determined polarization curves for anode and cathode areas, respectively.

The minus signs on the right hand sides of Eq. 4 and 5 are due to the fact that the potential in the electrolyte near the metal surface, ϕ, is equal to minus value of potential difference between the metal and the reference electrode (E), such as saturated calomel electrode, SCE. It is noted that the potential ϕ is defined with referring to the metal and has the inverse sign of the employed usually in the corrosion science.

Since the knowledge of physical quantities on the metal surface is important, boundary element method is employed here. The standard boundary element procedures lead to:

$$\kappa \, [H] \begin{Bmatrix} \phi_s \\ -f(i_a) \\ -f(i_c) \end{Bmatrix} - [G] \begin{Bmatrix} i_o \\ i_a \\ i_c \end{Bmatrix} = 0 \tag{6}$$

where the detail expression of matrices [H] and [G] are given in references [10] and the subscripts s, a, c and m represent the quantities on Γ_s, Γ_{m1} and Γ_{m2}, respectively.

Boundary element method is used to solve the Laplace's equation in Eq. 1 if the boundary conditions in Eq. 3 to 5 are known. Hence, ϕ and i on the whole metal surface can be determined.

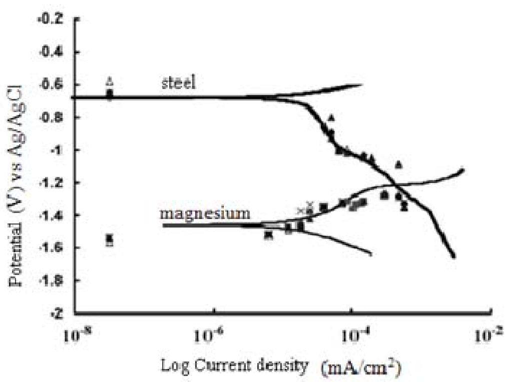

Figure 3. Polarization Curve of Steel and Magnesium vs Ag/AgCl [12]

Inverse Analysis Method

In this method, the optimum distance between pipe and anode is estimated from potential data distributions which are calculated on the pipe surface (Γ_{m2}). The inverse analysis is implemented by means of minimizing a cost function using GA. Cost function value defined as:

$$\varepsilon(\phi)=\sum_{l=1}^{N}\left[\left(\frac{\phi_l-\bar{\phi}_l}{\phi_{MAX}}\right)\right]^2 \tag{7}$$

where ϕ is the potential on the pipe surface nearest to anode, $\bar{\phi}$ is the potential on the pipe surface farthest to anode, N is the number of potential data on Γ_{m2}. ϕ_{MAX} is the highest potential value among N potential data. The values of potential are obtained by solving the Laplace's equation in Eq. 1 using BEM.

Application of GA

Genetic algorithm (GA) is an efficient search method based on the principles of natural selection. The algorithm is essentially a mathematical imitation of a biological process of the species evolution.

GA works with a population of individuals (chromosomes) that represent candidate solution to a problem. The chromosomes are usually represented by binary strings. Based on its fitness value, each chromosome of one generation undergoes evaluation, selection and recombination to form succeeding populations. This process is repeated for a predetermined number of generations. In the last generation, a chromosome will prevail, which represents the optimal solution to the examined problem.

The reciprocal value of $\varepsilon(\phi)$ in Eq. 7 is used to measure the fitness of each binary string as a candidate of the true potential distribution on the pipe from one generation (iteration) to the next. The iteration process of the analysis is terminated by satisfying one of the two conditions. They are (1) the number of generations in the GA process is reached; or (2) $\varepsilon(\phi)$ in Eq. 7 becomes smaller than the tolerance (ε_o). The distance between pipe and anode for such condition is the optimum distance for the protection system.

Example of Numerical Simulation and Discussion

To demonstrate the effectiveness of the propose method, the design of sacrifical anode cathodic protection system applying for the pipeline using ribbon sacrificial anode was analyzed. The cathodic protection system using ribbon anode shown in Fig.1 has been used extensively in the field [11]. The anode is deployed parallel along the pipe-line to maintain enough current flowing to the surface of pipeline for protecting the pipeline from corrosion attack. The optimal or effective cathodic protection system is achieved when the current density and potential values on the whole surface of the pipeline have certain values and the values are almost similar or well distributed along the surface of the pipeline.

Some parameters such as the soil conductivity, the distance of anode to object and the number of anode, affect the effectiveness of the cathodic protection system.

In this simulation, however, we limited only to simulate in order to obtain the optimum displacement between pipe-lines and anode and the influences of the soil conductivity to the optimum displacement. The two-dimensional model of cathodic protection using ribbon sacrificial anode is used as given in Fig. 2.

Some assumptions were made in developing the model, i.e. the cross-section shape of ribbon anode was simplified into circle shape, the experimental polarization curve for pipe and anode was taken from the reference (Fig. 3) and the soil domain was presumed to be one single domain. All parameters used for simulation are given in Table 1.

The cross-section of the pipeline is divided into four parts i.e. part A, B, C and D as shown in Fig. 4. Points p and q are the nearest and the farthest position of the pipeline to anode (r), respectively, and r is the distance between pipe and anode.

Table 1. Parameters for numerical analysis

Diameter of pipe, D	: 50 cm
Diameter of anode, d	: 1 cm
Soil	: $\kappa = 0.01\ \Omega^{-1}.m^{-1}$
	$\kappa = 0.007\ \Omega^{-1}.m^{-1}$
	$\kappa = 0.003\ \Omega^{-1}.m^{-1}$
	$\kappa = 0.00025\ \Omega^{-1}.m^{-1}$
	$\kappa = 0.00001\ \Omega^{-1}.m^{-1}$
Pipe material	steel
Anode	magnesium

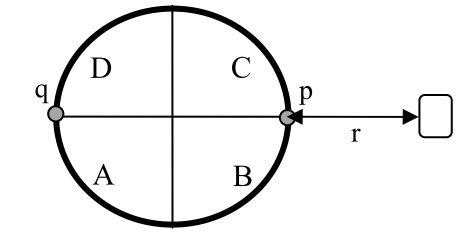

Figure 4. Cross-section of the pipeline divided into four parts.

Comparing the BEM-GA to the direct BEM, it shows that the error level of the BEM-GA is less than 10^{-5}. Thus, the BEM-GA has good compromise to use as as a tool in order to solve any corrosion cases.

The simulation results for the $\kappa = 0.007\ \Omega^{-1}.m^{-1}$, shows that the effective protection of pipe achieved when the distance between pipe and anode equal to 61.43 cm. The cost function for this condition is minimum as a result of the well distributed potential on the pipe surface (Fig. 5).

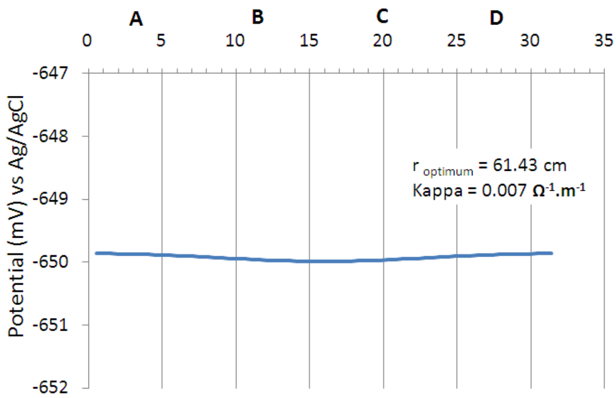

Figure 5. Potential distribution profile on the surface of pipe for r optimum ($\kappa = 0.007\ \Omega^{-1}.m^{-1}$).

Fig. 6 shows the effect of soil conductivity to the potential distributions profile on the pipe surface and to the $r_{optimum}$ that produces effective protection. It shows that the $r_{optimums}$ are gained when the potential distributions along the pipe surface almost similar or well distributed.

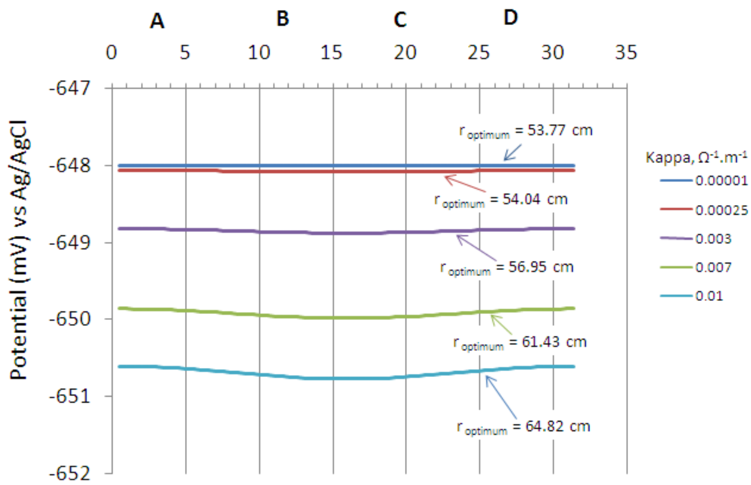

Figure 6. Potential distributions profile on the surface of pipe for various soil conductivity.

The relationship between soil conductivity and $r_{optimum}$ is given in Fig. 7. When the conductivity increases, the $r_{optimum}$ will wider in linear order. Therefore, it becomes easier to employ such protection system in various soil in order to generate effective protection.

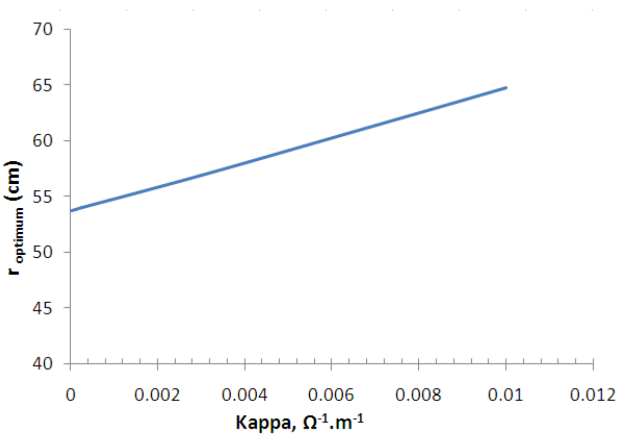

Figure 7. The influences of soil conductivity to the optimum displacement (r).

Summary

The cathodic protection system using ribbon sacrificial anode is evaluated by applying Boundary Element Method (BEM) and Genetic Algoritm (GA). The potential in the soil domain was modeled using the Laplace's equation. BEM was used to solve the Laplace's equation. Thus, the current density and potential on the whole pipe surface can be determined. GA was used to minimize the cost function in order to determine the optimum distance between pipe and anode for obtaining effective protection system. The result of BEM-GA simulation using a 2D model shows that the optimum distance between pipe and anode can be obtained using proposed method. Furthermore, the optimum distances are subject to change when the soil conductivity was changed.

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