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Simulation of Cathodic Protection on Reinforced Concrete Using BEM

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ABSTRACT

This study is to simulate the cathodic protection (CP) system on a reinforced concrete (RC) structure using the boundary element method (BEM). For simulation purposes, the RC domain was modeled by a Laplace equation. The boundary condition for the sacrificial anode and cathode (reinforcing steel) were obtained from its polarization curve. By solving the Laplace equation using BEM, all electrical potential values on the RC domain could be determined. Thus, the CP system could be evaluated based on the electrical potential on the reinforcing steel. Two studies were conducted by performing BEM simulation, where the CP system model and geometry for the studies were obtained from a previous researcher. The first study was to compare the simulation with experimental results. The second was to study the influence of several parameters on the electrical potential on the reinforcing steel. The BEM simulation results show that displacement between the anode and reinforcing steel would affect the electrical potential on the reinforcing steel. This was consistent with the experimental result. The simulation results also show that the anode size and conductivity of the concrete would affect the electrical potential on the surface of the reinforcing steel. Therefore, it is important to take account of those parameters in designing and/or evaluating the CP system for RC structures.

Keywords: *Cathodic Protection, Reinforced Concrete, BEM, Corrosion.*

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Introduction

Corrosion has become a worldwide problem. Losses due to corrosion have become a burden for every country. Every year, corrosion losses have reached 3–4% of the GDP of industrial countries [1]. Therefore, prevention of corrosion is necessary.

One of the sectors impacted by corrosion losses is infrastructure, which includes reinforced concrete (RC) structures. The losses caused by corrosion in this sector, including transportation and the utilities sector, have reached more than 70% of the total corrosion losses [2]. In addition, media reports have shown that the impact of corrosion on RC infrastructure has resulted in casualties, such as with the collapse of the Silver Bridge in the United States in 1967 [3], and the collapse of a toll road bridge in Canada in 2006 [4]. Thus, it is important to perform corrosion control and monitoring of RC structures [5].

A cathodic protection system is one of the most popular corrosion control techniques. The use of cathodic protection systems in RC structures has been widely reported [6]-[8]. However, the design and evaluation of the protection system is still a challenge for researchers and engineers. The linkage of parameters such as the resistance of electrolyte to the cathodic protection system of a RC structure still needs to be further understood as it can affect the performance of the system [8].

The development of numerical methods has progressed. One of these is the use of the boundary element method (BEM) for the simulation of galvanic corrosion [9]. More recently, BEM has also been used for simulating cathodic protection systems in marine [10]-[11] and underground environments [12]. The simulation results show that BEM is capable of showing the overall distribution of electrical potentials in the protected part. This will be helpful in both the design process and the evaluation of the cathodic protection system.

Therefore, this study aims to simulate a cathodic protection system on an RC structure using BEM. This is to study the effect of parameters such as anode size and concrete conductivity on the distribution of electrical potentials on the reinforcing steel surface.

BEM Formulation for Cathodic Protection

The cathodic protection system of a reinforced concrete (RC) structure is modeled as in Figure 1 (in concurrence with case study). This model consists of reinforcing steel and a sacrificial anode which was cast in a concrete environment. The sacrificial anode and the reinforcing steel are electrically connected in the model.

Then, it is assumed that there is no ion in-and-out of the cathodic protection model. Therefore, this system can be mathematically modeled by using the Laplace equation shown in Equation (1) [13]-[14]. This equation represents the electrical potential (ϕ) in the concrete domain.

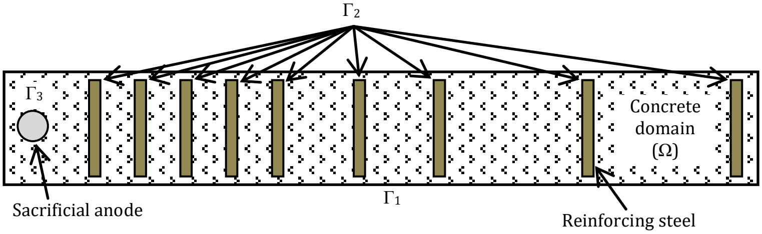


Figure 1: CP system on RC concrete model

The relationship between the electrical potential and the current density in the cathodic protection model is given in Equation (2). In this equation, i is the current density, κ is the conductivity of the concrete, and **n** is the normal vector.

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

$$i = -\kappa \frac{\partial \phi}{\partial \boldsymbol{n}} \qquad (\text{A/m}^2) \tag{2}$$

In order to solve Equation (1), the boundary conditions for the cathodic protection model must be known. The boundary condition for the concrete surface (Γ_1) is as shown in Equation (3), which is a result of the low value of the conductivity of the concrete.

$$i = i_0 = 0 \qquad (\text{A/m}^2) \qquad \text{on } \Gamma_1 \tag{3}$$

$$\phi = -f_c(i) \qquad (\text{V}) \qquad \text{on } \Gamma_2 \tag{4}$$

$$\phi = -f_a(i) \qquad (\text{V}) \qquad \text{on } \Gamma_3 \tag{5}$$

The boundary conditions for the reinforcing steel surface (Γ_2) and the anode surface (Γ_3) are obtained from each polarization curve and shown in Equation (4) and Equation (5), respectively. The polarization curve is the result of an experiment that shows the behavior of a metal when it is undergoing anodic and/or cathodic reaction. For simulation purposes, the cathodic polarization curve is used for the reinforcing steel and the anodic polarization curve for the sacrificial anode.

By following the procedure for the development of BEM as given in [9, 15] and using the given boundary conditions, Equation (1) can be solved.

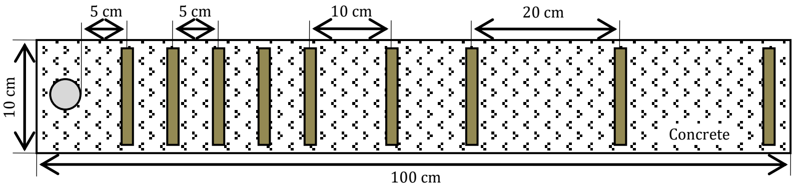
The procedure will obtain a matrix equation as given in Equation (6), for which the full details of the [H] and [G] matrices are given in [15].

$$\kappa[H]\begin{Bmatrix}\phi_{\Gamma 1}\\ -f_c(i)\\ -f_a(i)\end{Bmatrix}-[G]\begin{Bmatrix}i_0\\ i_c\\ i_a\end{Bmatrix}=0 \tag{6}$$

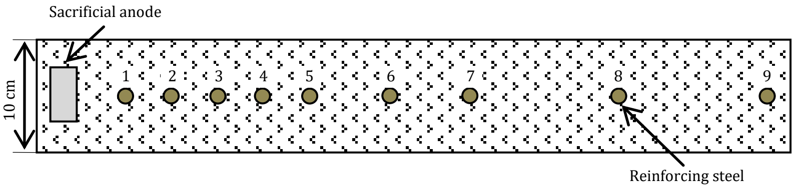
Thus, all the electrical potential values in the domain can be determined. The value of the electrical potential on the reinforcing steel surface will be used in the evaluation of the cathodic protection system.

Case Study

As an implementation of the BEM formulation for cathodic protection on the RC structure, a case study had been selected. This case study was derived from one of the works of Mahasiripan et al. [16]. Figure 2 shows a model of the cathodic protection system that is studied in this paper. The RC model was sized (10 × 10 × 100) cm. Nine reinforcing steel bars were cast in the concrete, each having a size of (9 × Φ1.2) cm. The displacement between the anode and the reinforcing steel is shown in the model.



Top view



Side view

Figure 2: Geometry of RC bar for simulation based on the work of [16]

The anode used in the simulation of cathodic protection was Mg anode. The Mg anode is in a more negative position in the galvanic series compared to the Al anode [17] that was studied by Mahasiripan et al. [16].

By using the Mg anode, it was expected that it might show more clearly the effect of various parameters on the distribution of electrical potential.

The boundary conditions for the Mg anode and reinforcing steel were derived from [18] as shown in Figure 3. The boundary condition for the Mg anode was the anodic polarization curve, whereas for the reinforcing steel it was the cathodic polarization curve as given in the figure. The electrical potential value given in the figure was converted into a value referring to the Cu/$CuSO_4$ reference electrode. The combination of electrical potential and the current density values of the polarization curve could be used as the boundary conditions for the Mg anode and cathode (reinforcing steel).

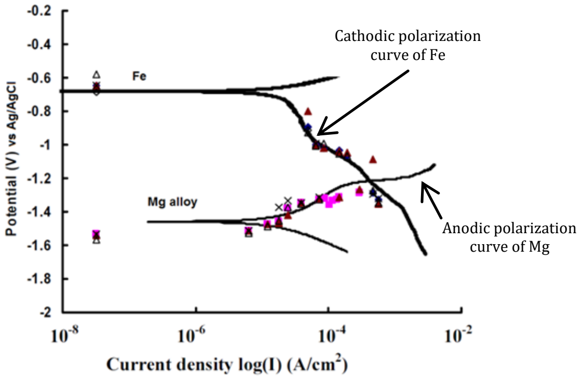


Figure 3: Polarization curves of Fe an Mg for CP boundary condition [18]

The first study was to compare the simulation result with the experimental result conducted by Mahasiripan et al. [16]. For simulation purposes, the Mg anode size and concrete conductivity values were (5 × Φ3) cm and 0.007 $\Omega^{-1}m^{-1}$.

Then, the second study was to study the effect of the anode size and concrete conductivity on the electrical potential distribution of the reinforcing steel, i.e. at the nearest and furthest point from the sacrificial anode. In the study, the anode sizes were (5 × Φ2.4) cm and (5 × Φ3) cm, while the value of conductivity of the concrete did not change for each anode size, and was 0.007 $\Omega^{-1}m^{-1}$.

The concrete conductivity values that were used to study the effect of conductivity were 0.007 $\Omega^{-1}m^{-1}$, 0.0229 $\Omega^{-1}m^{-1}$, and 0.1 $\Omega^{-1}m^{-1}$. The anode size parameter for each related conductivity was constant, with the size (5 × Φ2.4) cm.

The geometry and meshing (using triangle element) of concrete, reinforcing steel and anode were developed using Salome software. Total element for the whole component was 3057 element, i.e. 224, 2737, and 96 elements for concrete, reinforcing steel, and anode, respectively.

Results and Discussion

The simulation result using BEM for the first study is given in Figure 4. The distribution of electrical potentials on the reinforcing steel surface is shown in the figure. It is seen that the reinforcing steel adjacent to the anode obtained a more negative electrical potential value compared to further away from the anode.

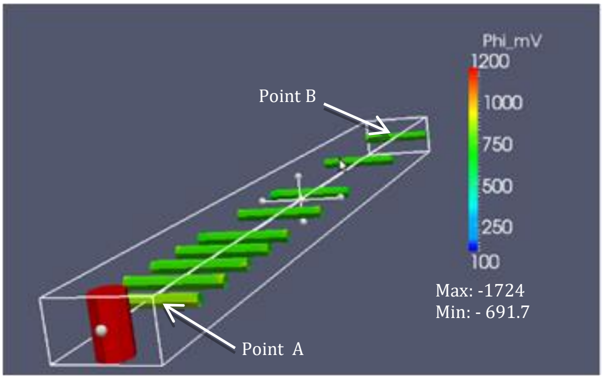


Figure 4: Electrical potential distribution on reinforcing steel using Φ3cm anode size and $\kappa = 0.007\ \Omega^{-1}m^{-1}$

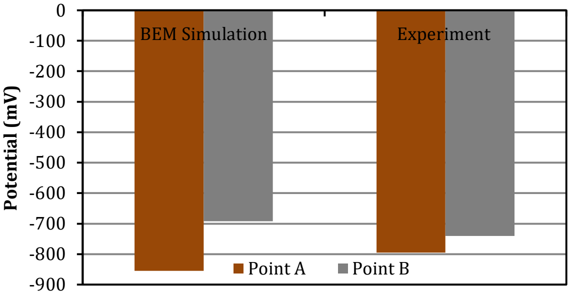


Figure 5: Comparison of BEM simulation (using Mg anode) and experiment (using Al anode) results

This distribution was consistent with the results obtained through experiments conducted by Mahasiripan et al. [16] as shown in Figure 5. The similarity of the trends between the simulation result and the experimental results was still obtained, even though the anode used in the simulation was Mg anode while Al anode was used in the experiment.

The simulation results using anode size Φ3 cm and Φ2.4 cm are shown in Figure 4 and Figure 6. The distributions of electrical potential on the reinforcing steel surface are shown in the figures. Based on one of the cathodic protection criteria, it is stated that the steel will be protected from corrosion if the electrical potential on its surface reaches ≤ -1130 mV (vs $Cu/CuSO_4$ reference electrode) [19]. By using this criterion, the cathodic protection for each anode size can be evaluated.

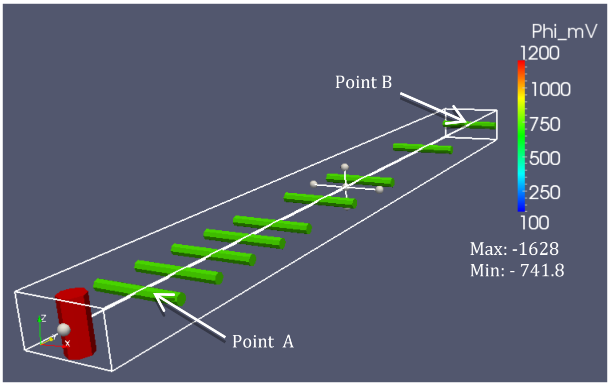


Figure 6: Electrical potential distribution on reinforcing steel using Φ2.4cm anode size and $\kappa = 0.007\ \Omega^{-1}m^{-1}$

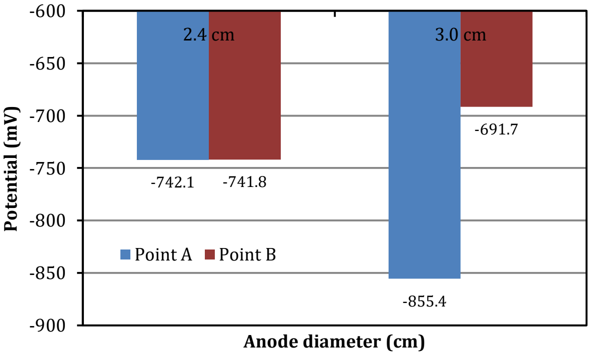


Figure 7: Comparison of simulation results of different anode sizes

The electrical potential value on the reinforcing steel when using an anode size of Φ2.4 cm was in the range -742.1 mV (point A) to -741.8 mV (point B) as shown in Figure 7. These values did not meet the required protection criterion. Meanwhile, the electrical potential value on the reinforcing steel for the anode size of Φ3 cm was in the range -855.4 mV (point A) to -691.7 mV (point B) as shown in Figure 7. This still indicates that the reinforcing steels adjacent to and far away from the anode are not sufficiently protected. However, the electrical potential of the reinforcing steels adjacent to the anode are significantly more negative when using the larger anode.

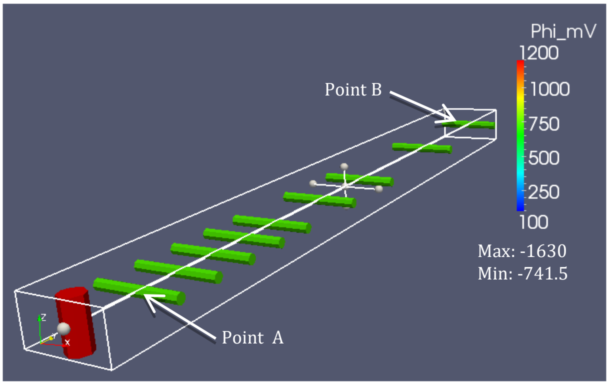


Figure 8: Electrical potential distribution on reinforcing steel using Φ2.4cm anode size and κ = 0.0229 $\Omega^{-1}m^{-1}$

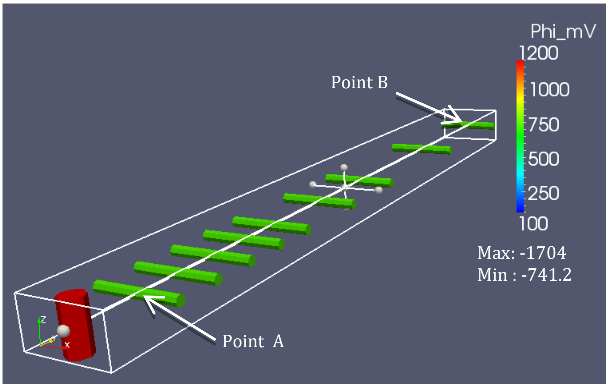


Figure 9: Electrical potential distribution on reinforcing steel using Φ2.4cm anode size and κ = 0.1 $\Omega^{-1}m^{-1}$

The simulation results show that the anode size might affect the electrical potential distribution on the reinforcing steel. Thus, the anode size should be considered in designing a cathodic protection system on RC structures.

The simulation results using the concrete conductivity of 0.007 $\Omega^{-1}m^{-1}$, 0.0229 $\Omega^{-1}m^{-1}$, and 0.1 $\Omega^{-1}m^{-1}$ are respectively shown in Figure 6, Figure 8 and Figure 9. The figures show the distribution of electrical potential values on the reinforcing steel surface. It can be seen that the overall simulation results give an electrical potential value of > -1130 mV. Therefore, the RC structure has not been adequately protected from corrosion.

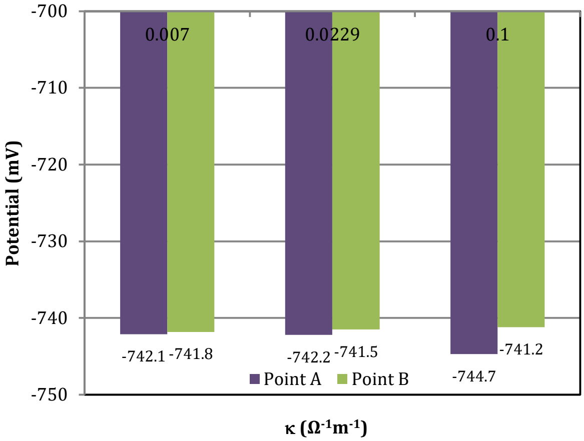


Figure 10: Comparison of simulation results of different concrete conductivity

However, the three simulation results show the effect of concrete conductivity on the electrical potential value of the reinforcing steel surface, as shown in Figure 10. The figure shows that increasing the concrete conductivity value might cause the electrical potential value on the reinforcing steel nearest the anode to become more negative. On the other hand, by increasing the conductivity, the electrical potential value on the furthest reinforcing steel becomes more positive. This might be due to the high conductivity of concrete being able to assist the current density become more easily concentrated into the nearest reinforcing steel to the anode.

The simulation results show that the size of anode and the conductivity of concrete might affect the electrical potential distribution on the reinforcing steel. By increasing the size of the anode, the electrical potential value on the reinforcing steel near the anode becomes more negative, so that the protection criterion can be achieved. However, the electrical potential on the reinforcing steel that is far away from the anode could be more positive with the increasing anode size. Therefore, an optimization might be required to obtain the best anode size.

Meanwhile, it is also necessary to pay attention to the concrete conductivity value. High concrete conductivity values, such as in submerged RC structures, could result in a larger difference of the electrical potential between the nearest and the farthest reinforcing steels from the anode. This would certainly affect the effectiveness of the cathodic protection system. Hence, in designing a cathodic protection system for RC structures, the effect of the conductivity needs to be considered.

Conclusions

The simulation of the cathodic protection (CP) system on a reinforced concrete (RC) structure using the boundary element method (BEM) was conducted in this study. Two studies were performed by BEM. The first study was to compare the simulation with experimental results. The second was to study the influence of the anode size and concrete conductivity on the electrical potential on the reinforcing steel. The results show that the simulation was consistent with the experimental result. The displacement between the anode and reinforcing steel affects the electrical potential on the reinforcement. Furthermore, the simulation results show that the electrical potential on the surface of the reinforcing steel will be affected by the anode size and the conductivity of the concrete. Hence, it is important to consider these parameters in designing and/or evaluating the CP system for RC structures.

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