Simulation the effect of anode-cathode displacement and anode type on reinforced concrete cathodic protection using BEM

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Abstract. The aim of the study is to simulate the effect of anode-cathode displacement and anode type on the potential distribution of reinforced concrete (RC) cathodic protection (CP) system using boundary element method (BEM). For the simulation, Laplace equation was used to model the RC domain. The boundary conditions for the anode and cathode (reinforcing steel/rebar) were represented by its polarization curve. By using BEM, the electrical potential values on the whole domain should be calculated. Therefore, the effects of those parameters were studied based on the rebar electrical potential. For the study, the CP system model and geometry were obtained from a previous researcher. The BEM simulation results show that the anode-cathode displacement affects the distribution of electrical potential on the protected reinforcing steel. It was consistent with the previous research result. The results also show, as expected, that the anode type influences the electrical potential value on the rebar. Hence, those parameters should be considered in designing and/or evaluating the RC CP system.

1 Introduction

Corrosion is the phenomenon of metal deterioration because of its interaction with the environment. It already becomes a worldwide problem. Every year, 3–4% of the global GDP has been wasted due to corrosion [1].

The infrastructure sector is one of the sectors that impacted by corrosion. It includes reinforced concrete (RC) structures. In this sector, the losses have reached more than 70% of the total corrosion losses [2]. Furthermore, the media have reported that the corrosion on RC infrastructure has resulted in casualties. The examples are 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 and necessary to perform corrosion control and monitoring of RC structures [5], and also to conduct corrosion detection [6].

Cathodic protection (CP) is one of the popular corrosion control methods. The method is also implemented on RC structures. The use of the method has been widely reported [7-9]. However, researchers and engineers still challenged in exploring the field of designing and evaluating of the protection system [10]. The effect of parameters on the CP system of the RC structure still necessary to be further understood because of might influenced the performance of the system [9].

Numerical method is one of the tools for solving various engineering problems that has progressed significantly. One of the methods is boundary element method (BEM) that has been used of the for the

simulation of galvanic corrosion [11]. BEM has also been utilized to simulate CP systems in marine [10, 12-13] and underground environments [14]. The results show that the distribution of electrical potentials in the protected structures could be performed by BEM. This capability will be beneficial in both the design process and the evaluation of the CP system.

Previous research has conducted a simulation to study the influence of anode size and concrete conductivity to the RC CP system [10]. The influence of other parameters still needs to be understood. Therefore, this research aims to simulate a cathodic protection system on an RC structure using BEM in order to study the effect of anode-cathode displacement and anode type on the distribution of electrical potentials on the reinforcing steel.

2 BEM formulations for RC CP

The system of CP for an RC structure is modeled as depicted in Figure 1. The RC model consists of reinforcing steel/rebar and sacrificial anode. The rebar and the anode are electrically connected in the RC model.

For the RC model, an assumption is made that the CP system has no ion in-and-out. Thus, the system might be mathematically modeled by using the Laplace equation as given in Equation (1) [15-16]. The equation represents the electrical potential (ϕ) for the whole concrete domain (Ω).

The electrical potential (ϕ) and the current density (i) for the whole domain of the RC model is having a

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relationship as given in Equation (2). In this equation, κ is the conductivity of the concrete, and $\mathbf{n}$ is the normal vector.

$$\nabla^2 \phi = 0 \quad \text{in } \Omega \quad (1)$$

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

Fig. 1. RC CP system model.

Some boundary conditions (BC) of the RC model have to be known for solving Equation (1). Those boundary conditions are shown in Equation (3) – (5). For the concrete surface (Γ_1), the BC is as given by Equation (3). The zero value of current density is as a result of the very low conductivity of the concrete.

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

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

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

Furthermore, the BC for the rebar (Γ_2) and the anode (Γ_3) surfaces are generated from each polarization curve. These BCs are shown in Equation (4) and Equation (5), respectively. The polarization curve represented the behavior of a metal when it is undergoing anodic or cathodic reaction and obtained from an experiment. Boundary element method (BEM) was developed by following the procedure as given in [11, 17]. The procedure might result in an equation as Equation (6). The full details of the [H] and [G] matrices could be found in reference [17].

$$\kappa[H] \begin{Bmatrix} \phi_{\Gamma_1} \\ -f_c(i) \\ -f_a(i) \end{Bmatrix} - [G] \begin{Bmatrix} i_0 \\ i_c \\ i_a \end{Bmatrix} = 0 \quad (6)$$

Thus, Equation (1) can be solved by using BEM with BC in Equation (3) – (5). All the electrical potential and current density values for the whole RC domain can be determined by executing BEM. For the evaluation of CP of RC, the electrical potential value on the rebar surface will be utilized.

3 Case study

A case study had been selected for this study. The case study was derived from the works of Dodds et al. [18]. Figure 2 shows the CP system for RC that is simulated in this study. The geometry of RC model was $(80 \times 10 \times 10)$ cm. A rebar was cast in the concrete that has a size of $(61 \times \Phi 2.5)$ cm. The positioning of rebar and anode in the concrete are as shown in the model of Figure 2. The anode used for the simulation of cathodic protection was having the geometry of $(6.5 \times \Phi 3)$ cm.

The development of geometry and meshing (using triangle element) of concrete, rebar, and anode were using Salome software. Total element for the whole component was 1376 element, i.e. 852, 498, and 26 elements for concrete, rebar, and anode, respectively.

Fig. 2. The geometry of RC for simulation based on the work of Dodds et al. [18].

Fig. 3. Polarization curves of Fe and Zn [19].

Fig. 4. Polarization curves of Fe and Mg [20].

The first simulation was to study the effect anode-cathode displacement to the distribution of electrical potential on rebar surface, i.e. at the nearest and furthest point from the anode. For simulation purposes, the Zn

anode was used, and the concrete conductivity value was $0.007 \Omega^{-1}\text{m}^{-1}$.

The BC for the Zn anode and rebar were derived from [19] as shown in Figure 3. The BC for the Zn anode was the anodic polarization curve, whereas for the rebar was the cathodic polarization curve as shown in the figure. The anode-cathode displacements used for this study were 5 cm; 10 cm; and 20 cm.

Then, the second simulation was to study the effect of the anode type on the electrical potential distribution of the rebar. In the study, the Zn and Mg anodes were used for the study. While, the concrete conductivity value and anode-cathode displacement did not change for each anode type, i.e. $0.007 \Omega^{-1}\text{m}^{-1}$ and 20 cm respectively.

The BCs for rebar and Zn anode were the same with first simulation. While, for rebar and Mg anode, the BCs were generated from [20] as seen in Figure 4. In the simulation, the electrical potential value of Figure 3 and Figure 4 were already converted into a value referring to the Cu/CuSO₄ reference electrode.

4 Results and discussion

By using the BC as described in the previous section, BEM was executed in order to obtain electrical potential on the surface of rebar. Figure 5, Figure 6 and Figure 7 show the simulation results for the first simulation. The electrical potential distributions on the rebar surface are shown in the figures. For all figures, those show that the rebar part adjacent to the anode had a more negative electrical potential compared to the farthest part from the anode. This pattern was consistent with the previous research that conducted by Mahasiripan et al. [21] and Fonna et al. [10].

Fig. 5. Electrical potential distribution on rebar using Zn anode for 5 cm anode-cathode displacement.

Figure 5 shows the simulation result using 5 cm anode-cathode displacement. In the figure, it is seen that the distribution of electrical potential on the surface of the rebar is between -922.4 to -919.6 mV. The most negative potential value is on the surface of rebar that closest to the sacrificial anode (point A).

Figures 6 and 8 show the distribution of electrical potential values on the surface of the rebar with anode-cathode displacement 10 and 20 cm. The potential

distribution value for the 10 cm anode-cathode displacement is between -921.3 to -919.6 mV. As for the 20 cm anode-cathode displacement is in the range -920.7 to -919.6 mV. Both images also show that the most negative value is in the part of the nearest reinforcing steel from the sacrificial anode (point A).

Fig. 6. Electrical potential distribution on rebar using Zn anode for 10 cm anode-cathode displacement.

Moreover, the effectiveness of the cathodic protection system in protecting corrosion can be evaluated from the electrical potential value with following existing standards and also the uniformly distributed potential value. The potential value of protection follows the NACE standard. Meanwhile, the uniform or uneven distribution of electrical potentials can be observed through the magnitude of the potential difference between the maximum and minimum potential values. The smaller difference in value, the electrical potential distribution becomes more evenly distributed.

Fig. 7. Electrical potential distribution on rebar using Zn anode for 20 cm anode-cathode displacement.

In this study, the effect of anode-cathode displacement is analyzed based on the electrical potential difference value. The calculation results for the electrical potential differences were 2.8 mV for the 5 cm anode-cathode displacement; 1.7 mV for the 10 cm anode-cathode displacement; and 1.1 mV for the 20 cm anode-cathode displacement. The comparison between those results can be seen in Figure 8.

Fig. 8. The comparison of simulation results for different anode-cathode displacement.

Based on the electrical potential difference, it can be stated that the smaller the anode-cathode displacement might result in the uneven distribution of potential. Conversely, the greater the anode-cathode distance could result in a more equitable distribution of potential. However, it is estimated that there will be an optimum anode-cathode displacement that will provide a best potential distribution within the protection criterion. Thus, further research needs to be conducted to study the optimum anode-cathode displacement.

Fig. 9. Electrical potential distribution on rebar using Mg anode for 20 cm anode-cathode displacement.

Fig. 10. The comparison of simulation results for different anode type.

The second simulation results using Mg anode is shown in Figure 9. While, using Zn anode is in Figure 7. In Figure 9, it can be seen that the electrical potential

distribution on the surface of the rebar is between -768 to -741.8 mV. Same as before, the most negative potential value is on the rebar that closest to the anode. Thus, it still consistent with the previous research result [10, 21].

The comparison of the electrical potential distribution between Zn anode and Mg anode is shown in Figure 10. The figure shows that Zn anode could provide more negative electrical potential than Mg anode. Hence, Zn anode might give more protection.

Therefore, simulation results show that the anode type, for sure, might affect the electrical potential distribution on the rebar. Hence, in designing and/or evaluating a cathodic protection system for RC structures, the effect of anode-cathode displacement and anode type need to be considered.

5 Conclusions

The simulation of the CP on an RC structure using the BEM was conducted in this study. From the results of the study, it can be concluded that:

- The anode-cathode displacement affects the electrical potential on the rebar.
- The electrical potential on the surface of the rebar might be affected by the anode type.
- It is important to consider those parameters in designing and/or evaluating the CP system for RC structures.

However, it is important to study on the optimum anode-cathode displacement for the CP system.

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