The influence of some solution candidate on the performance of boundary element inverse analysis in detecting rebar corrosion

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Abstract. The purpose of this research is to study the effect of some solution candidate to the performance of boundary element inverse analysis (BEIA) that utilized for detecting corrosion of reinforcing steel/rebar in concrete. BEIA was developed by combining the boundary element method (BEM) and particle swarm optimization (PSO). BEM was used to calculate the electrical potential on the whole domain of reinforced concrete. While PSO was to optimize cost function to detect the rebar corrosion in concrete. BEIA was applied by using several measured electrical potential data as a reference such as from half-cell potential measurement. Numerical simulation on reinforced concrete with single rebar show that the increase of some solution candidate would resulting in increasing the number of iterations for the solution become convergence. However, the average error from the actual solution would be smaller by increasing solution candidate number. Therefore, the number of solution candidate affect the performance of BEIA in detecting rebar corrosion in concrete.

1. Introduction
Corrosion is one of natural phenomenon that became the culprit of several structural failures especially reinforced concrete (RC) structure. Among the failures were the collapses of Silver Bridge in the USA, 1967[1], a toll road bridge in Canada, 2006 [2], and Atlantis Water Adventure Taman Impian Jaya Ancol in Indonesia, 2011 [3]. Hence, the corrosion of rebar/reinforcing steel in concrete is important to be detected early to prevent premature failure of the structures [4].

Half-cell potential mapping technique is one of the popular methods for evaluating rebar corrosion in concrete. The application and result interpretation of this method is based on ASTM C876 standard. However, the method has some limitation, i.e., need a large amount of data to be accurate [5], time-consuming and laborious [6], and only provided the possibility of corrosion will occur [7]. Therefore, the method is needed to be improved to overcome the limitation.

Boundary element inverse analysis (BEIA) is among promising technique to solve the limitation of half-cell potential mapping. In the previous study, BEIA was developed by combining boundary element method (BEM) and particle swarm optimization (PSO) which had shown the capability in detecting rebar corrosion [8-9]. The influence of weight inertia on the performance of the method also
had been explored [10]. However, the effect of some solution candidate to the performance of BEIA in detecting rebar corrosion is still unclear. Therefore, it is important to be investigated.

This research aims to study the effect of some solution candidate to the performance of BEIA for detecting reinforcing steel corrosion in concrete. A simple RC with single rebar and corrosion was used as a case study in the research.

2. Rebar corrosion model in concrete

Rebar corrosion in concrete is modeled as shown in figure 1. Single rebar is cast in the concrete. There is single corrosion (anode) that located on the rebar. While others part of rebar are cathodes. For this model, the electrical potential ($\phi$) for the whole RC domain ($\Omega$) is represented by the Laplace equation as in equation (1) [8-11].

The relationship between current density ($i$) and electrical potential ($\phi$) for the whole concrete domain should follow equation (2) [8-11]. In equation (2), $\kappa$ is the domain conductivity, $n$ is the outward normal unit, and $\partial/\partial n$ is the derivative in the normal direction.

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

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

The boundary conditions for the model in figure 1 are given as in equations (3-5). In equation (3), the current density ($i$) on the concrete surface ($\Gamma_1$) was constant and for the model was set equal to zero due to the low conductivity of concrete. While the boundary condition on anode and cathode were governed by each polarization curve which correlating electrical potentials ($\phi$) and current density ($i$), i.e., equation (4) for the cathode ($\Gamma_2$) and equation (5) for the anode ($\Gamma_3$) of rebar.

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

$$\phi = -f_a(i) \text{ (V) on } \Gamma_2$$

$$\phi = -f_c(i) \text{ (V) on } \Gamma_3$$

Laplace equation might be solved using BEM. The procedure of BEM formulation can be followed in [12]. By following the procedure, the unknown $\phi$ and $I$ on the surface of the concrete and rebar can be calculated.

3. Boundary element inverse analysis for rebar corrosion detection

For the rebar corrosion detection, some boundary conditions, regarding figure 1, were unknown such as size and location of corrosion. Therefore, BEIA technique by combining BEM and PSO to detect RC corrosion was proposed in previous work [8-10]. The algorithm of combining BEM and PSO was shown as in figure 2. The procedure of BEIA was described in the reference [8]. The solution candidates were called particles in the method.
For each particle of the iteration, the cost function ($\varepsilon$) was evaluated by using equation (6). In this equation, $C$ is the rebar corrosion profile (such as the size and location of corrosion), and $N$ is the number of measured electrical potential data that used in BEIA. $\phi$ and $\bar{\phi}$ are the calculated electrical potential using BEM and measured electrical potentials such as using half-cell potential technique, respectively. $\phi_{max}$ is the highest electrical potential value among $N$.

$$\varepsilon(C) = \sum_{j=1}^{N} \left( \frac{\phi_j - \bar{\phi}}{\phi_{max}} \right)^2$$ (6)

The updating position and velocity of particles for each iteration were based on the particles local best and global best as follow equations (7–8). For this equations, $X_{j+1}$ = next particle position, $X_j$ = current particle position, $V_{j+1}$ = next velocity, $V_j$ = current velocity, $W$ = inertia weight, $a_1$ and $a_2$ = constants, $r_1$ and $r_2$ = random numbers (0–1), $p_{best}$ = local best particle, $g_{best}$ = global best particle, and $j$ = iteration.

$$X_{j+1} = X_j + V_{j+1}$$ (7)

$$V_{j+1} = WV_j + a_1r_1(p_{best} - X_j) + a_2r_2(g_{best} - X_j)$$ (8)

**Figure 2.** Algorithm of BEIA which combine BEM and PSO.
4. Case study

To study the effect of the number of solution candidate to the performance of BEIA, a simple block of RC was used. Single reinforcing steel was cast into the block and only had one corrosion. Figure 3 shows the RC block that used for the study where the 3D model was simplified into an a2D model for the simulation.

![3D model](image1)

![2D model](image2)

**Figure 3.** RC block which used as the case study in the research.

As shown in figure 3, the size and location of corrosion were unknown. These parameters would be detected by using BEIA. Some numbers of solution candidates were used to study its effect on the detection performance of BEIA. Moreover, several constant parameters that used in the simulation are \( \kappa = 0.007 \, \Omega^{-1} \cdot \text{m}^{-1} \); \( \varepsilon_0 \leq 10^{-4} \); \( a_1 = a_2 = 0.5 \); \( N = 15 \) and \( W = 0.25 \). The boundary condition for anode and cathode followed the equations (9-10) [6] respectively that generated from its polarization curve [13].

\[
\phi_a = 0.600 - 10i \quad \text{(V)} \quad (9) \\
\phi_c = 0.270 - 10i \quad \text{(V)} \quad (10)
\]

For measured electrical potential data (\( \bar{\phi} \)) on concrete surface, it was taken from BEM simulation using the model in figure 3. In this simulation, the corrosion size was 2 cm and the corrosion location was at 50 cm. Figure 4 shows the electrical potential distribution on concrete surface and 15 data were used as measured electrical potential data (\( \bar{\phi} \)) in BEIA simulation.

5. Numerical simulation results and discussion

BEIA simulation results for 5 and 30 solution candidates are shown in figure 5 and 6, respectively, i.e., for 1st until 20th iteration. In the figures, it shows that all particles were randomly distributed on the searching space for the 1st iteration. By increasing number iteration, the particles moved to a certain position of searching space. It occurred on all number of solution candidates. Thus, almost all solution candidates were already positioned on the same place on 12th iteration. It means that corrosion was starting to be detected.
However, the cost function of some solution candidates for a certain number of solution candidates still did not reach $\varepsilon_0$ yet. When the cost functions of all solution candidates were $\leq \varepsilon_0$, then corrosion (the solution of the problem) was detected. It contained corrosion size and corrosion location. It was found that corrosion was detected on 11\(^{th}\) and 23\(^{rd}\) iteration for 5 and 30 solution candidates, respectively.

Thus, the simulation was performed for a solution candidate of 2, 10, 20, and 50. The results for all simulation are summarized in figure 7. The figure shows the influence of the number of solution candidates to the number of iteration in finding the solution and the average error from the actual solution. By increasing the number of solution candidate, the average error from the actual solution becomes smaller. The error value was < 5\% for the number of solution candidate $\geq$ 20. However, the computational effort, indicated by the number of iteration in finding the solution, became higher by increasing the number of solution candidate. Thus, the compromise must be taken that is the error < 5\% and the computational effort acceptable. For this case, the number of solution candidate which fulfill such criteria is 20 until 30 particles.

![Figure 5. The moving of each particle in detecting the size and location of corrosion using five solution candidates: (a) 1\(^{st}\) iteration; (b) 4\(^{th}\) iteration; (c) 8\(^{th}\) iteration; (d) 12\(^{th}\) iteration; (e) 16\(^{th}\) iteration; and (f) 20\(^{th}\) iteration.](image-url)
Figure 6. The moving of each particle in detecting the size and location of corrosion using 30 solution candidates: (a) 1st iteration; (b) 4th iteration; (c) 8th iteration; (d) 12th iteration; (e) 16th iteration; and (f) 20th iteration.

6. Conclusions
In this research, the influence of some solution candidate to the performance of BEIA for detecting rebar corrosion in concrete was studied. BEIA was developed by combining BEM and PSO. BEIA was performed by using several electrical potential data as a reference. Numerical simulation results show that the increase in the number of solution candidate would give in increasing the number of iterations for the solution become convergence. Meanwhile, the average error from the actual solution would be smaller by increasing solution candidate number. Hence, the number of solution candidate affects the performance of BEIA in detecting rebar corrosion in concrete. The number of solution candidate that gives average error ≤ 5% and iteration for finding solution ≤ 25 are 20 until 30 particles.
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