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A quantitative analysis of the geometric effects of reinforcement in concrete resistivity measurement above reinforcement

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HIGHLIGHTS

- This work presents the estimation of concrete resistivity above reinforcement.
- Geometric effect (GE) predicts quantitatively the effect of reinforcement.
- The prediction of GE is based on a resistivity method.
- Apparent resistivity rate estimates the concrete resistivity above reinforcement.

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ABSTRACT

This study aims to quantitatively estimate the geometric effect of steel bar on the resistivity measurement above reinforcement as a method of evaluating concrete resistivity. For this purpose, the geometric effect is evaluated by the resistivity estimation model (REM) that estimates the apparent resistivity above the reinforcement. This REM as a mathematical model reflects the resistivity of concrete and reinforcement, as well as the cover depth, the bar diameter, and electrode intervals. Based on this evaluation, this study proposes a geometric effect (GE) rate, which is the quantitative index determined by the geometric factors of reinforcement. It also experimentally examines the applicability of the apparent resistivity rate to diagnose the concrete resistivity. Based on the results of this study, the GE rate is expected to be useful for estimating the geometric effects of reinforcement.

1. Introduction

The corrosion state of reinforcing bar in concrete structures is accelerated or restrained depending on the environmental factors that surround the reinforcement. Factors that affect corrosion status include internal elements, such as dissolved oxygen and ions, water, pH, and temperature within the pores in concrete [1]. The resistivity of the concrete that surrounds the reinforcement is, therefore, dependent on the corrosive environment and can be used as an index for evaluating the durability of concrete structures.

As for the methods used to diagnose corrosion deterioration, the electrochemical techniques of the half-cell potential and polarization resistance have generally been used [2–4]. However, these methods require local destruction such as cover concrete chipping.

On the other hand, the resistivity method for estimating concrete resistivity provides a nondestructive technique for evaluating the corrosive environment [5]. However, the apparent resistivity measured above the reinforcing bar cannot be used for estimating the concrete resistivity because the effect of reinforcing bars has not been considered in such approaches. The exact estimation of concrete resistivity therefore requires the method that provides a quantitative analysis of the reinforcement alone. Although various studies on the quantitative analysis [6–9] of the influence of reinforcement have been carried out, the obtained results have not been verified experimentally.

The objective of this study is to quantitatively estimate the geometric effect of reinforcement on the resistivity and develop the convenient method to estimate concrete resistivity. To this end, the geometric effect (GE) rate generated by the resistivity estimation model (REM) [10] is proposed to represent the relationship between the apparent resistivity, which is affected

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by reinforcement, and the resistivity of concrete alone. The REM, a mathematical model that estimates the apparent resistivity above the reinforcement, reflects the resistivity of concrete and reinforcement, as well as the concrete cover depth, the bar diameter, electrode intervals, etc. In addition, the apparent resistivity rate related to the proposed GE rate was discussed in order to experimentally verify the validity of the proposed method for resistivity analysis.

2. Analytical basis

2.1. Apparent resistivity

The apparent resistivity is normally measured by considering the geometric array of electrodes and the relationship between the applied current, I, and the response potential, V, applied to the current electrodes and the potential electrodes installed on the measurement surface. The resistivity method for concrete resistivity measurement generally employs the Wenner electrode array, shown in Fig. 1, which consists of two outer current electrodes located at points C_1 and C_2 and two inner potential electrodes placed at points of P_1 and P_2 on the measurement surface at the same interval of a.

The apparent resistivity is usually calculated in the following manner: First, the potential Φ_1, determined at point P_1 by current sources I_{C1} (+I) and I_{C2} ($-I$) is written as Eq. (1):

$$\Phi_1 = \frac{\rho I}{2\pi}\left(\frac{1}{C_1P_1} - \frac{1}{C_2P_1}\right) \tag{1}$$

Potential Φ_2 can then be determined at point P_2 in the same manner. The potential difference generated by the applied current I between potential electrodes P_1 and P_2 is written as Eq. (2):

$$V = \Phi_1 - \Phi_2 = \frac{\rho I}{2\pi}\left(\frac{1}{C_1P_1} + \frac{1}{C_2P_2} - \frac{1}{C_2P_1} - \frac{1}{C_1P_2}\right) \tag{2}$$

Eq. (2) for a semi-infinite isotropic homogeneous medium can be simply rewritten as Eq. (3) to provide the resistivity, as follows:

$$\rho = 2\pi a\, V/I \tag{3}$$

where $a = 1/\left(\frac{1}{C_1P_1} + \frac{1}{C_2P_2} - \frac{1}{C_2P_1} - \frac{1}{C_1P_2}\right)$, and $2\pi a$ is the coefficient of the electrode configuration that represents the geometric characteristics of Wenner's electrode array.

However, because Eq. (3) represents the case in which the medium is homogeneous and has resistivity ρ, it cannot be applied to the case of a heterogeneous medium. To deal with this problem, the concept of apparent resistivity ρ_a, written as Eq. (4), is introduced to provide a rough estimate of the resistivity distribution of a measurement subject, as follows:

$$\rho_a = 2\pi a \frac{V}{I} \tag{4}$$

2.2. Apparent resistivity obtained by REM

The reliability of concrete resistivity estimation for concrete structures can be increased when the scope of the estimation includes the effects of reinforcement as well as those of concrete. In order to reflect the effects of reinforcement, it is necessary to assess the apparent resistivity along with geometric effects such as the concrete cover, diameters of reinforcement, and intervals of electrodes when making an evaluation.

The resistivity estimation model (REM) [10] was proposed to incorporate the effect of reinforcement into an interpretation of resistivity [10]. This model employs a mirror method to identify changes in the apparent resistivity caused by two media having different resistivities, such as concrete and a reinforcement material. In particular, a resistivity reflection coefficient is defined to apply the mirror method to a cylindrical model, such as a model of reinforcement. The resistivity reflection coefficient represents the relationship between the current source and the image charge, which is assumed to be a mirror-image generated by that current source by using the method of images [11,12].

The REM formulated by using the method of images finds the position and the size of the image charge generated by the current source against the boundary. It also finds the position and the size of the new image charge generated by this image source. The apparent resistivity is theoretically calculated based on the sum of the response voltages on the electrode, which are affected by this current source and image charges [10].

As shown in Fig. 2, two current electrodes and two potential electrodes are respectively placed at the inner and outer positions above the reinforcement at the same interval of a. As shown in Fig. 3, on the surface of concrete, the current source (+)I_{C1} is placed at a point C_1 in a parallel direction to the reinforcing bar such that it then generates an image charge at point D_{11} inside the reinforcement material against the surface S_1, which is the boundary surface between the concrete and reinforcement. In addition, the image charge at point E_{11} is generated by the image charge at point D_{11} against the surface S_2. Similarly, image charges are infinitely generated at points D_{1n} and E_{1n}. Therefore, the potential V_{11} at point P_1 affected by the point current source I_{C1} is represented as Eq. (5).

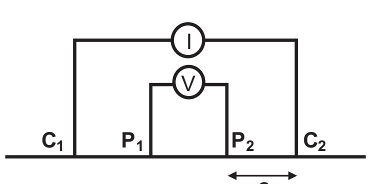

Fig. 1. Resistivity measurement method: Wenner array.

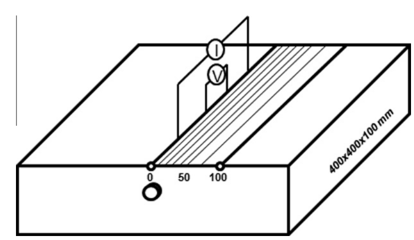

Fig. 2. Geometry of specimen and measurement direction.

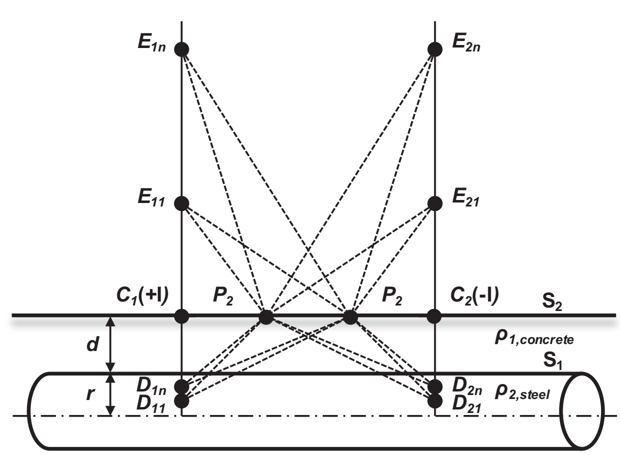

Fig. 3. Resistivityestimation model (REM) using mirror method.