Advanced Resistivity Method for Corrosion Evaluation Directly above a Reinforcement Bar

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ABSTRACT

This study aims to develop a completely nondestructive system to diagnose corrosion deterioration in reinforced concrete structures; the system employs a resistivity method that involves no structural damage. It is highly desirable to perform measurements on concrete directly above the reinforcement under analysis so as to collect information on concrete around that reinforcement.

KEYWORDS: Corrosion, Completely Nondestructive Method, Resistivity, and Concrete Structure

1. INTRODUCTION

The rate of steel corrosion in concrete structures is controlled by three mechanisms: anodic control, cathodic control, and resistance control (JSCE 2000). Among these mechanisms, resistance control, which is based on the void percentage and moisture content of concrete, predominantly governs the corrosion rate of reinforcing steel when the regions of anodic and cathodic corrosion are located at some distance from each other. Therefore, by understanding the state of the electrolytes involved in the corrosion reaction and by obtaining information that enables us to indirectly evaluate the corrosion environment surrounding reinforcement, we can gain insight into the concrete resistivity.

Concrete resistivity, which is one of the physical properties of concrete, has previously been determined by performing resistivity measurements on concrete structures; the measurements are carried out in accordance with the Wenner method, which involves the arrangement of two current and potential electrodes each on the concrete surface (Polder et al. 2000). When using this method, researchers have conventionally carried out the measurements at unreinforced areas that are located away from the object reinforcement. However, when the objective of diagnosis using concrete resistivity is to obtain knowledge about the corrosion environment at a particular area on the understanding that a potential risk of corrosion deterioration exists in that area, indirect evaluation of a specific area on the basis of measurements performed at another distant area may reduce the accuracy of any judgments in this regard.

Recently, a completely nondestructive technique was developed for determining the concrete resistivity and polarization resistance using the apparent resistivity measured above a reinforcement bar; this technique was reviewed for its applicability in evaluating concrete durability (Lim et al. 2009a, 2009b).
However, performing corrosion estimation using the resistivity method and the polarization resistance is a complicated task because the resistivity must be replaced by the resistance. Therefore, in order to apply the resistivity method as a completely nondestructive technique, it is necessary to evaluate the corrosion state in terms of the resistivity.

The objective of this study is to introduce a corrosion evaluation method in which the resistivity method employed for the concrete surface above a specific steel reinforcement bar is utilized to estimate the resistivity of the surface of the bar.

2. RESISTIVITY ESTIMATION MODEL (REM)

For carrying out corrosion assessments using a completely nondestructive technique, it is highly desirable to perform the measurements on the area of concrete directly above the reinforcement. The resistivity estimation model (REM), as expressed in Eq. (1), is used for estimating the resistivity when a circumferential system with a resistivity of \( \rho_2 \) exists directly below a semi-infinite isotropic homogeneous medium with a resistivity of \( \rho_1 \), as shown in Fig. 1 (Lim et al. 2009a). The REM, which is a mathematical model that is developed using the mirror method, combines Wenner’s method involving conventional four-electrode measurements of resistivity with geometric parameters including cover depth \( d \), reinforcement radius \( r \), and electrode interval \( a \), in addition to the resistivity of concrete and the reinforcement.

\[
V_a = \frac{d\varphi_1}{\pi a} \left[ 1 + \sum_{n=1}^{\infty} \frac{Q_n}{\Gamma_n} \left( \frac{1}{1+\frac{r^2}{d^2}} - \frac{1}{1+\frac{(r+n)^2}{d^2}} \right) \right]
\]

Here,

\[
\varphi_1 = \frac{r}{1+2(n-1)d} \quad (2)
\]

\[
Q_n = \frac{k_2(k_2-k_1)}{k_2^2+k_1^2} \quad (3)
\]

\[
\Gamma_n = \frac{3+(1-k_2^2)}{2} \quad (4)
\]

\[
Q_n = \frac{2n \varphi_1}{a} \quad (5)
\]

Furthermore, \( V_a \) denotes the apparent potential difference (V); \( \rho_1 \), the concrete resistivity (Ω·m); \( \rho_2 \), the steel resistivity (Ω·m); \( d \), the cover depth (m); \( r \), the reinforcement radius (m); and \( a \), the electrode interval (m).

The REM is analyzed in order to understand the effects of the geometrical factors that are considered in the measurement of the apparent resistivity. Figure 2(a)-(b) shows the changes in terms of the response voltage (V) that are caused by changing the electrode interval (\( a = 0.02, 0.03, \) and \( 0.04 \) m), concrete cover depth (from 0.01 to 0.1 m), and reinforcement diameter (from 0.01 to 0.05 m) while maintaining the concrete resistivity (\( \rho_1 \)) and reinforcement resistivity (\( \rho_2 \)) constant at 100 Ω·m.
and 0 Ω m, respectively. The homogeneous state without reinforcement was also indicated in the figure to compare the effect of reinforcement.

With regard to the effect of the electrode intervals, the response voltage (V) decreases as the interval increases, approaching 0 V as the interval approaches infinity. The response voltage rapidly increases with the cover depth in the beginning but gradually levels off, converging with the response voltage for homogeneous concrete without reinforcement. This result is related to the current path at the time of measurement, i.e., the volumetric ratio of reinforcement to concrete within the range of measurement; the result indicates that the current flows only through concrete as the distance between the measuring point and the reinforcement increases. Although the response voltage (V) decreases as the bar diameter increases, the differences are smaller than those in the case of the cover depth, presumably because the volumetric change within the current-carrying range is smaller in the case of the bar diameter than in the case of the cover depth.

\[
\begin{array}{c}
\text{Fig. 2 Simulation of response voltage related to geometric parameters.}
\end{array}
\]

3. EQUIVALENT CIRCUIT MODEL BASED ON THE RESISTIVITY METHOD

Figure 3 shows the equivalent circuit model (Lim et al. 2009b) that is constructed on the basis of the resistivity method using Wenner’s electrode configuration; in nondestructive methods for the quantitative evaluation of corrosion, this model is used to define the relationship between the electrodes, which are oriented parallel to the steel bar and located at equal intervals on the concrete surface, and the boundary between concrete and steel.

This circuit model consists of the concrete resistances on the left (R_{cL}) and right (R_{cR}) and the concrete resistance in the center (R_{cC}). The geometric distribution resistance corresponds to the effects of the spatial components and resistibilities in a semi-infinite medium (R_g), and the concrete homogeneity resistance is assumed as the degree of homogeneity of the resistivity (R_i), the capacitance of the electrical double layer (C), and the polarization resistance as the charge transfer resistance (R_p).

When using the resistivity method, the corrosion of the reinforcement bar is evaluated on the basis of the value of the boundary impedance (Z_b); in the present model as well as the polarization resistance method (Andrade et al. 1978), the Z_b value is calculated using the capacitance (C) and the
polarization resistance ($R_p$). In this study, the equivalent circuit model constructed using the resistivity method provides a basis for the applicability of the proposed method to corrosion diagnosis.

![Nyquist plots](image)

(a) Polarization method: $R_p$ ($\Omega \cdot \text{cm}^2$). (b) Resistivity estimation method: $\rho_{\text{steel}}$ ($\Omega \cdot \text{m}$).

As shown in Fig. 4(a), when using the polarization resistance method, a low-frequency current (i.e., a low-frequency voltage) should be supplied in order to determine the diameter of the Nyquist plot semicircle because the measurement area over the reinforcement is large (Feliu et al. 1988); supplying a low-frequency current implies that a large measurement period is required. In contrast, when using the resistivity estimation method, the peak of the semicircle can be obtained in the high-frequency range; consequently, the measurement period can be decreased (Zhang et al. 2001), as illustrated in Fig. 4(b).

Furthermore, when using the resistivity estimation method, the measurement region in concrete becomes clear. To further explain this point, the polarization resistance method is characterized by an ambiguous measurement region that lies between the electrode on the concrete surface and the steel bar with a wire lead connected to it after the concrete cover has been removed. However, in the resistivity method, the measurement region of the inner concrete is limited by the positions of the two current electrodes. Therefore, the resistivity method clarifies the measurement region of the boundary surface between concrete and the steel bar at specific positions, and it consequently improves the reliability of corrosion tests.

4. CONCLUSION

In this study, it was shown that the resistivity method was introduced for the corrosion evaluation in concrete structures. It is anticipated that on account of its completely nondestructive nature, this newly developed resistivity method will enhance the reliability and applicability of corrosion diagnoses.

REFERENCES


