Scientific paper

Corrosion Evaluation by Estimating the Surface Resistivity of Reinforcing Bar

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Abstract

The corrosion rate of steel embedded in concrete is evaluated using polarization resistance assumed on the boundary between concrete and steel. However, the previously established polarization resistance method requires the removal of the concrete cover to connect the steel with a wire lead, and it takes a long time for the measurement of corrosion. This study proposes a new method for the nondestructive testing of deterioration caused by corrosion in concrete structures by estimating the surface resistivity of steel. For this purpose, the resistivity on the surface of a steel bar is assumed to behave similarly to the polarization resistance with the progress of corrosion. The resistivity of the steel surface is estimated using the resistivity estimation model (REM), and it is used as an index of the corrosion state. The REM is a mathematical model that considers geometric factors influencing the measurement, such as the cover depth, reinforcement radius, and electrode interval, and it can be used to estimate the resistivities of the concrete and steel bar in concrete structures. In addition, the possibility of applying this resistivity estimation method is investigated by performing an experiment on the accelerated corrosion of steel.

1. Introduction

With regard to the corrosion diagnosis of concrete structures, many studies have considered their half-cell potential (ASTM C876 1991) and polarization resistance (Andrade et al. 1978). Among the techniques used for corrosion diagnosis, the polarization resistance method is appropriate for the evaluation of corrosion because it is based on electrochemical analysis; however, it requires the removal of a concrete cover and connection of a wire lead to a steel bar inside the concrete. In addition, there are problems to be addressed in the measurement and evaluation of corrosion because of the difficulty in defining the region of steel included for measurement.

On the other hand, the resistivity method involves the measurement of the resistivity of concrete to determine the corrosion environment of steel (Polder et al. 2000). This method is a nondestructive method that hardly damages the concrete under examination. However, in the past, this method has been used to evaluate the corrosion environment only in the region of concrete where steel does not influence the measurements. That is, the method was unable to directly evaluate the concrete surrounding steel in which there is a high risk of corrosion. Studies on a method for corrosion measurement with the presence of specific steel below the surface of the concrete have been conducted; however, the practical applicability of this method has not been reviewed (Monterio et al. 1998; Zhang et al. 2001; Zhang et al. 2002).

Recently, a nondestructive technique was developed for determining the concrete resistivity and polarization resistance from the apparent resistivity measured above a reinforcement bar, and it was reviewed for its applicability in evaluating concrete durability (Lim et al. 2009a, 2009b).

The evaluation of corrosion by using the polarization resistance with the resistivity method, however, complicates the corrosion estimation process 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 propose an evaluation method of corrosion by estimating the resistivity of the steel surface in the resistivity method on the concrete surface above a specific reinforcement bar.

2. Theoretical background for corrosion testing

2.1 Equivalent circuit model for resistivity

As shown in Fig. 1, the equivalent circuit model (Lim et al. 2009b) based on the resistivity method with Wenner’s electrode configuration is used to define the relationship of the electrodes, which are oriented parallel to the steel on the concrete surface at equal intervals, and the boundary between concrete and steel for the nondestructive quantitative evaluation of corrosion.

This circuit model consists of the left concrete resis-
The right concrete resistance ($R_{cr}$), the right concrete resistance ($R_{cR}$), the concrete resistance in the center ($R_C$), the geometric distribution resistance expressing the effects of spatial components and resistivities in a semi-infinite medium ($R_g$), the concrete homogeneity resistance assumed as the degree of homogeneity of the resistivity ($R_i$), the capacitance of the electrical double layer ($C$), and the polarization resistance of the charge transfer resistance ($R_p$).

Using the resistivity method, the corrosion of reinforcement bar is evaluated by the state of the boundary impedance ($Z_b$) consisting of the capacitance ($C$) and the polarization resistance ($R_p$) in this model as in the polarization resistance method (Andrade et al. 1978). In this study, the circuit model based on the resistivity method provides a basis for its applicability to corrosion diagnosis.

As shown in Fig. 2(a), the polarization resistance method requires a low-frequency current (voltage) to determine the diameter of a Nyquist plot semicircle because the measurement area over the reinforcement is large (Feliu et al. 1988), and it also requires a long measurement period. In contrast, since the resistivity estimation method can obtain the peak of the semicircle in the high-frequency range, it is therefore possible to shorten the time required for the measurement (Zhang et al. 2001), as illustrated in Fig. 2(b).

And the region of measurement in concrete becomes clear. In the polarization resistance method, the region between the electrode on the concrete surface and the steel bar with a wire lead connected after the removal of the concrete cover is ambiguous. However, in the resistivity method, the region of the inner concrete is limited by the two current electrodes. Therefore, the resistivity method clarifies the region of the boundary surface between the concrete and the steel bar in specific spots, and it improves reliability in corrosion testing.

### 2.2 Resistivity estimation model (REM)

For a corrosion assessment by using a completely non-destructive technique, it is most desirable to measure concrete directly above the reinforcement. The resistivity estimation model (REM) as expressed in Eq. (1) is used for estimating the resistivity when a circumferen-

tial 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. 3 (Lim et al. 2009a). The REM, which is a mathematical model using the mirror method, combines Wenner’s method as conventional four-electrode measurement of resistivity with geometric parameters including cover depth, reinforcement radius, and electrode interval in addition to the resistivity of concrete and reinforcement.

The unknown values of the resistivity of concrete and reinforcement are estimated with the minimal error method using the known values of geometric parameters.

\[
V_s = \frac{\rho_1}{\pi d} \left[ \frac{1}{2} + \sum_{n=1}^{\infty} \left[ k_n \frac{\sum_{n=1}^{\infty} \frac{Q_n}{k_n}}{\left[ \frac{1}{1+H_1^2} \right]^2 - \frac{1}{(4+H_1^2)^2}} + \frac{\sum_{n=1}^{\infty} \frac{Q_n}{k_n}}{\left[ \frac{1}{1+G_1^2} \right]^2 - \frac{1}{(4+G_1^2)^2}} \right] \right]
\]

where,

\[
k_n = \frac{r}{(1+2(n-1)d+r}
\]
\[ Q_n = \frac{k_n(\rho_2 - \rho_1)}{\sqrt{k_n\rho_2 + \rho_1}} \quad (3) \]
\[ H_n = \frac{d + r(1 - k_n)}{a} \quad (4) \]
\[ G_n = \frac{2nd}{a} \quad (5) \]

and

- \( V_C \): Apparent potential difference (V)
- \( \rho_c \): Concrete resistivity (Ω m)
- \( \rho_s \): Steel resistivity (Ω m)
- \( d \): Cover depth (m)
- \( r \): Reinforcement radius (m)
- \( a \): Electrode interval (m).

### 3. Experimental outline

#### 3.1 Specimen

As shown in Fig. 4, mortar specimens with an embedded steel bar were fabricated in self-made molds with dimensions of 100 × 100 × 400 mm. Mortar (cement-to-sand ratio of 1:2) was produced with a 60% water-to-cement (W/C) ratio. Normal Portland cement and river sand (density: 2.58g/cm³, percentage of water absorption: 2.21%) were used. For accelerating electrolytic corrosion, chloride ions (Cl–) were included in the mortar at a weight ratio of 3 kg/m³ of cement.

The φ13 mm round bar with mill scale used in this study was cut to a length of 41 cm. A wire lead at one side of the rebar steel was connected for inducing electrolytic corrosion and measuring half-cell potential after the acceleration corrosion. In addition, the steel bar was coated with epoxy resin (thickness: 3.5 cm) on both sides in order to exclude electric leakage from the wire lead and other external influences.

Two specimens, A and B, were manufactured under the same conditions to compare changes in the steel surface resistivity (hereafter, "steel resistivity") for each level of corrosion; these specimens were demolded 24 h after placement and cured for 45 days in water at 20°C.

#### 3.2 Test apparatus

The water content in mortar, which influences the measurement results, must be constantly maintained during the measurement. Therefore, all sides of each specimen, except for the measurement side (upper side) and the opposite side (lower side), were coated with epoxy resin to prevent moisture loss through the surface. In addition, since the measurement must be repeated at the same location, the exact location was indicated on the concrete surface before the start of measurement. Surface drying before and after application of the epoxy resin was conducted at 20°C and 55% humidity. After drying of the epoxy resin, the specimens were cured again for two days in water.

Electrodes used for measurement were manufactured using a conductive gel with \( 8.3 \times 10^{-6} \) Ω m resistivity.

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### 3.3 Experimental procedure

This resistivity estimation method was proposed for the...
completely nondestructive evaluation of corrosion deterioration in concrete structures. The resistivity estimation method quantitatively evaluates corrosion using the steel resistivity by converting the concept of polarization resistance assumed on the boundary surface between concrete and steel.

In the corrosion acceleration experiment, the corrosion level was determined from the assumed corrosion loss based on the weight loss of the steel bar, and an anode current density of 0.72 mA/cm² was produced on the surface of the steel using a constant current generator. Two specimens were directly connected to allow identical currents to flow in both specimens.

Electric current, which increases the accumulated corrosion rate with time, was applied to each specimen for the assumed corrosion loss of 0–1.0% to a corrosion loss level in steps of 0.25%; it was applied after the assumed corrosion loss of 1.0% to a corrosion loss level in steps of 0.5%, cracks (at a corrosion loss of approximately 2.5% in this experiment) appeared on the specimen surface, as listed in Table 1.

To determine the corrosion level of steel, two types of monitoring were carried out. First, the voltage monitoring of electrolytic corrosion involved measuring the voltage between the copper plate in the solution of a pool installed on the upper part of a specimen and the steel of the anode in the specimen in real time. After the termination of electrical corrosion for each corrosion level, the moisture on the surface was removed and the specimens were left in a natural state for about an hour. Second, the half-cell potential was monitored through measurement at five locations spaced at 5 cm intervals along the steel on both sides of the center of each specimen.

After the half-cell potential was measured, the complex apparent resistivity was measured in the frequency range of 0.1 to 1000 Hz after electrolytic corrosion except for the initial sound state. For this complex resistivity, 1 mA of sinusoidal current was used for each measuring frequency, and a 5 kHz low-pass I/O filter was used to remove noise during measurement. The electrode interval was 2, 3, and 4 cm. The complex resistivity for each corrosion level was measured repeatedly until cracks occurred on the surface. Refer to the previous study (Lim et al. 2009b) for further details on the corrosion acceleration experiment and measurement method.

### Table 1 Test specimens and assumed corrosion levels.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Accumulated corrosion loss rates</th>
<th>Assumed corrosion loss level</th>
</tr>
</thead>
<tbody>
<tr>
<td>A, B</td>
<td>From sound state of zero to 1%</td>
<td>0.25% step</td>
</tr>
<tr>
<td></td>
<td>After 1% until point of cracking</td>
<td>0.50% step</td>
</tr>
</tbody>
</table>

Fig. 6: Induced anodic voltage for specimens A and B.
have been corrosive according to electrolytic corrosion. When cracks occurred, the half-cell potential dropped even further to –500 mV (vs. CSE).

4.3 Complex resistivity

Figure 8 shows the apparent resistivity and phase difference measured at each electrode interval (a = 2, 3, and 4 cm) for two experiments when the steel bar is in sound condition. The apparent resistivity had similar trends for specimens A and B. The larger the interval between electrodes, the greater the change in apparent resistivity with frequency change. This is because the larger the electrode interval, the larger the boundary surface between the concrete and steel. The effect of frequency dependence is extremely small at a = 2 cm. The phase difference is also found to increase as the electrode interval increases. In this experiment, the maximum phase difference was approximately 1 Hz. Therefore, the steel resistivity in the resistivity estimation method must be estimated from the results obtained by measurement at the frequency of 1 Hz with a large electrode interval.

Figure 9 for a Nyquist plot as a complex interpretation shows the trends of changes in apparent resistivity and phase difference due to corrosion acceleration. There is a maximum imaginary value in the Nyquist plot at frequencies near 1 Hz as the maximum phase differences. The radius of the semicircle as the steel resistivity of the reinforcing bar decreases with the progress of corrosion in the Nyquist plot. This indicates that corrosion assessment could be done by using the resistivity estimation method whenever the boundary surface between concrete and steel has a various passivation behavior in concrete structures.

5. Corrosion evaluation by estimation of steel resistivity

The resistivity of concrete and steel can be estimated by using the REM (Eq. (1)) from the response voltage measured by the resistivity estimation method. The concrete resistivity, which corresponds to mortar resistivity,
is estimated from the response voltage measured in the high-frequency range. The steel resistivity is then estimated using the estimated concrete resistivity above and the response voltage measured in the low-frequency range.

In this study, the concrete resistivity was estimated from the response voltage measured with electrode intervals of a = 2, 3, and 4 cm using a sinusoidal current of high frequency at 100 Hz. In addition, the steel resistivity was estimated by using the response voltage at a low frequency of 1 Hz, which indicates the size (radius of the semicircle) of the polarization resistance as the maximum imaginary value, as described in Fig. 2(b), with relatively large electrode intervals of 4 cm in this experiment.

The estimated concrete resistivity increases with the progress of electrolytic corrosion, as illustrated by Fig. 10. Such a trend was reported in previous studies (Lim et al. 2009a); however, since the objective of this study is to estimate corrosion using the resistivity of concrete and steel, the increase in concrete resistivity is not examined. The concrete resistivity indicated to the low values, which are very high corrosive level (Langford & Broomfield 1987) in concrete, because specimens were subjected to water curing to stabilize their moisture content.

At the frequency of 100 Hz, the steel resistivities estimated with the concrete resistivity were 10 and 7.80 Ω·m for specimens A and B, respectively. According to the corrosion acceleration experiment, these resistivities approached 0 Ω·m. However, the steel resistivity at the

![Fig. 9 Nyquist plots for the electrode interval of 4 cm at different corrosion rates.](image)

![Fig. 10 Estimated concrete resistivity for specimens A and B at different corrosion rates.](image)

![Fig. 11 Steel resistivity estimated at different corrosion rates for the electrode interval of 4 cm.](image)
high frequency of 100 Hz is included in the steel resistivity estimated at the low frequency of 1 Hz as shown by the Nyquist plot. Therefore, the steel resistivity at the high frequency was not considered in this study.

The steel resistivity as an index of quantitative evaluation of corrosion in this study was estimated by using the REM from the concrete resistivity and the response voltage at the low frequency of 1 Hz. As shown by Fig. 11, the resistivities indicated 30 \( \Omega \cdot m \) and 27.9 \( \Omega \cdot m \) for specimens A and B at the assumed corrosion loss of 0%, respectively, and decreased with increasing assumed corrosion loss as a change of the polarization resistance. The values approached zero closer to an internal crack.

The results of this study suggest that the resistivity estimation method using the concept of the surface resistivity of steel can be used to evaluate the corrosion of reinforcement as in the polarization resistance method. This new method is expected to enhance the reliability and the applicability of the diagnosis of corrosion in concrete structures because it is completely nondestructive.

6. Conclusions

In this study, a resistivity estimation method that employs both the technique of the resistivity method and the concept of the steel surface resistivity was proposed for the quantitative evaluation of the corrosion of reinforcement as a completely nondestructive measurement approach for concrete structures. The results of this study are as follows.

1. The two frequencies used for the estimation of resistivity can be decided through complex resistivity interpretation. The concrete resistivity that corresponds to the medium can be found in the high-frequency range from the small phase differences. The steel surface resistivity for corrosion can be found in the low-frequency range from the large effect of the boundary surface between concrete and steel. In this study, frequencies of 100 Hz and 1 Hz were used for estimating the resistivities of the concrete and steel bar.

2. The electrode interval must be decided according to the geometric conditions of the reinforcing bar. In particular, since the steel resistivity must be estimated from the response voltage in the low-frequency region, the electrode interval must be sufficient to include the boundary surface between concrete and steel.

3. The steel resistivity estimated from the apparent resistivity clearly decreased with the progress of corrosion. At the points of cracks that resulted from an increase in the amount of corrosion substances in the specimens, the steel resistivity dropped to approach 0 \( \Omega \cdot m \). From this result, it was found that the resistivity estimation method regarding corrosivity evaluation could quantitatively evaluate corrosion as in the polarization resistance method.

4. Although this experiment was performed in a laboratory, the resistivity estimation method is expected to provide a new nondestructive method for the evaluation of concrete durability.

Acknowledgments

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References


