Formulation of a Nondestructive Technique for Evaluating Steel Corrosion in Concrete Structures

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This paper reports on a fundamental study on the formulation of a corrosion evaluation system for reinforced concrete structures based on a completely nondestructive technique. This is a method of evaluating the polarization resistance produced at the boundary between concrete and steel, without destroying the concrete surface, to estimate the resulting corrosion current density. A method of estimating the resistivity distribution within concrete to examine the steel corrosion environment is also proposed. This system consists of an equivalent circuit, a resistivity model for examining the effect of concrete, i.e., the measurement medium, and an actual measurement system. The equivalent circuit takes account of the electrode arrangement for resistivity measurement, and the impedance within concrete. This technique was verified by tests using specimens with controlled corrosion losses and was proven to express corrosion deterioration within concrete well. Evaluation by this technique was thus found feasible.

KEY WORDS: corrosion; steel; completely nondestructive technique; equivalent circuit; polarization resistance; concrete resistivity.

1. Introduction

Corrosion in a reinforced concrete structure is a deterioration phenomenon that not only mars the safety and reliability of the structure but also directly leads to increases in the cost related to its maintenance and reductions in its service life. In order to prevent corrosion-induced damage, electrochemical methods including the half-cell potential method, polarization resistance method, and A.C. impedance method have been applied to studies and field practice as major techniques for corrosion diagnosis. The half-cell potential method is most frequently used on site among others due to the simplicity of measurement and analysis compared with other methods. However, as all electrochemical phenomena within the concrete are included in the output, it requires considerations to eliminate the effects of other conditions to solely evaluate the corrosion phenomenon.

In contrast to this, the polarization resistance method and A.C. impedance method evaluate corrosion by forced polarization of the electrical properties on the boundary between concrete and reinforcement using external voltage or current. This permits the calculation of the instantaneous corrosion current density related to the corrosion deterioration of steel reinforcement, with which the service life of concrete structures in terms of durability is predicted. However, there are some problems in the determination of the effective measurement area at the boundary between concrete and reinforcement for calculating polarization resistances and the requirement of long time measurement caused by the effects of the assumed capacitance at this boundary.

On the other hand, the resistivity method for evaluating the corrosive environment for concrete structures is a nondestructive technique of measuring the resistivity of concrete, which is one of its physical properties, by setting two outer current electrodes for applying current and two inner voltage electrodes for measurement, thereby minimizing damage to concrete. In other words, in contrast to the above-mentioned methods which involve chipping of cover concrete, this method enables nondestructive evaluation. Moreover, limiting of the measurement area by the two outer current electrodes permits diagnosis in a small area. Nevertheless, measurement by the resistivity method in actual sites is carried out not around steel reinforcement of concern about corrosion but at areas judged as being unaffected by reinforcement. For this reason, evaluation in terms of the resistivity of concrete expressing the potential of reinforcement corrosion remains on the level of indirect estimation, without reaching the level of judgment based on the electrochemical characteristics of corrosion.

In order to evaluate the electrochemical corrosion properties of the boundary between concrete and reinforcement by a completely nondestructive technique, Monteiro et al. have conducted studies related to a technique to apply the resistivity method to concrete surfaces directly above reinforcement in recent years. This technique is based on a concept simultaneously considering an equivalent circuit model expressing the electrochemical characteristics of corrosion, such as polarization resistance, and the effect of geometric factors that result from the application of the resistivity method. However, no specific evaluation system from ac-
tual measurement to corrosion judgment has been proposed yet.

This study aims to formulate a diagnosis system whereby corrosion deterioration in reinforced concrete structures can be evaluated using a resistivity method without damages in structural frames as a completely nondestructive technique. To this end, a corrosion evaluation system was hereby formulated for calculating the polarization resistance and investigating the distribution of concrete resistivity.

For this formulation, an equivalent circuit incorporating the geometric factors of the resistivity measurement method was assumed for the quantitative evaluation of the corrosion of steel. In addition, the resistivity model that can estimate the resistivity of the concrete directly above reinforcement is used to evaluate concrete resistance as a factor of the equivalent circuit. Then electrolytic corrosion tests inducing losses in corrosion mass were carried out for the reinforcement of specimens in order to prove the feasibility of this technique.

2. Assumption of an Equivalent Circuit Model

An equivalent circuit was configured based on the corrosion evaluation concept by the A.C. impedance method, assuming the geometric characteristics of the resistivity measurement method using four electrodes on the measurement surface.

2.1. Equivalent Circuit of the Boundary by A.C. Impedance Method

For an equivalent circuit at the boundary between concrete and reinforcement, Randle’s model is generally employed for its simplicity of analysis. It includes the capacitance (C) expressing the electrical double layer in parallel with the polarization resistance (R_p), which are connected in series with the solution resistance of concrete (R_s) as shown in Fig. 1.

The boundary impedance (Z_{AC}) is expressed as:

$$Z_{AC} = R_s + \left( \frac{1}{R_p} + j\omega C \right)^{-1} = R_s + \frac{R_p}{1 + j\omega CR_p} \quad \ldots \ldots (1)$$

Substituting j\omega into \omega,

$$Z_{AC} = R_s + \frac{R_p}{1 + \omega^2 C^2 R_p^2} - j\omega CR_p^2 \quad \ldots \ldots (2)$$

(it should be noted that \(j = \sqrt{-1}\)).

The effect of the concrete solution resistance connected in series (R_s) should be eliminated to grasp only the changes in the impedance at the boundary due to corrosion. The concrete solution resistance (R_s) is therefore measured by a high frequency band, which is scarcely charged in the capacitance at the boundary (C) and can thus be regarded as in a short-cut condition, while the effects of concrete solution resistance (R_c) and polarization resistance (R_p) are measured by a low frequency band in which the capacitance (C) is charged. In corrosion evaluation, the polarization resistance (R_p) is determined from the difference between the resistances at both frequencies based on these measurements, thereby carrying out quantitative evaluation of corrosion. This polarization resistance (R_p) is the diameter of the semicircle of a Nyquist plot used for complex analysis and tends to decrease as corrosion proceeds.

2.2. Equivalent Circuit Model for Corrosion Evaluation by Resistivity Measurement

Figure 2 shows an equivalent circuit assumed for the resistivity measurement method used in the present completely nondestructive technique for evaluating corrosion deterioration in reinforced concrete structures. The equivalent circuit consists of a combination of the measurement system including four electrodes for sending and receiving electrical signals and a measuring device and the impedance system including concrete and embedded steel as the object of measurement.

In the measurement system, two outer current electrodes of the concrete surface and two inner voltage electrodes are placed at equal intervals according to the electrode arrangement by the Wenner method. Constant current is input in the current electrodes by the measuring device, while the internal state is measured from the voltage electrodes. The control and recording related to the series of measurements are carried out by the measuring device.

The impedance system consists of the concrete resistance in the left (R_{cl}), concrete resistance in the right (R_{cr}), concrete resistance in the center (R_n), geometric distribution resistance (R'_g), boundary impedance (Z_{gb}'), and the resistance of the conductor part of reinforcement (R_{ag}).

The use of sinusoidal current source allows the assumption that the same amount of current as the current source is supplied to each of the concrete resistances in the left and right (R_{cl} and R_{cr}). The evaluation can therefore be carried out without taking account of these for the impedance calculation. The concrete resistance in the center (R_n) represents the physical and geometrical properties, such as the resistivity, moisture content, and void percentage of concrete as physical factors, as well as the effects of concrete cover depth, reinforcement diameter, and electrode intervals, as geometrical factors.

The geometric distribution resistance (R'_g), which expresses the effects of spatial components distributed in various forms and resistivities in a semi-infinite medium, is as-
sumed to be infinite (∞) when the resistivity within concrete is homogeneous, and all of the current is assumed to flow toward the concrete resistance in the center (R_c). When there is an effect of geometrical inhomogeneity, such as reinforcement, the geometric distribution resistance is assumed to become variable between infinite (∞) and 0 Ω, causing current partition in parallel with the concrete resistance (R_c).

For the boundary impedance (Z'_b), which is a primary object of corrosion evaluation, Randle’s model shown in Fig. 1 was adopted to simplify the properties of the boundary between concrete and reinforcement. The concrete homogeneity resistance (R'_c) is assumed to express both the degree of homogeneity of the resistivity from the surface inward and the effect of pore solution in contact with reinforcement for each interval between electrodes.

The polarization resistance (R'_p), which is a charge transfer resistance, is connected in parallel with the capacitance of the electrical double layer (C') and tends to decrease as corrosion proceeds. Conversely, the capacitance (C') is reported to increase as corrosion proceeds. The resistance of the conductor part of reinforcement (R_g) is assumed to be a conductor with a resistance of 0 Ω.

The applied current is a sinusoidal current. When this current flows toward the geometric distribution resistance (R'_c) among the paths in the equivalent circuit, it takes paths similar to the trajectories of the frequency bands in the A.C. impedance method. In other words, a high frequency current flows through the electric double layer (C') and tends to decrease as corrosion proceeds. Conversely, a low frequency current charges the electric double layer (C') and then flows through the polarization resistance (R_p). Corrosion evaluation is qualitatively and quantitatively carried out by calculating the polarization resistance, which is in inverse proportion to the corrosion current density, utilizing the dependence to frequency at the boundary.

Figure 3 shows a simplified form of the equivalent circuit shown in Fig. 2. These are theoretically equivalent to each other as explained below:

The boundary impedance on one side of reinforcement and concrete (Z'_b) is expressed as Eq. (3), where ω is 2πf (f is frequency).

\[ Z'_b = R'_b + \left( \frac{1}{R'_p + \omega C'} \right)^{-1} = R'_b + \frac{R'_p}{1 + \omega C' R'_p} \]  

The impedance sum (Z'_gb) of Eq. (3) and the geometric distribution resistance (R'_g) is expressed as Eq. (4).

\[ Z'_gb = R'_g + Z'_b = R'_g + R'_b + \frac{R'_p}{1 + \omega C' R'_p} \]  

The impedances (Z'_gb) on both sides are connected in series with the resistance of the conductor part of reinforcement (R_g). Since steel is a more highly conducting material than concrete, the resistance of the conductor part of reinforcement (R_g) is assumed to be 0 Ω, and therefore the impedance is doubled (Z'_gb). If this is assumed to be impedance Z_t, then

\[ Z_t = R_{st} + 2Z'_gb \]  

where R_{st}→0.

By substituting each element as follows,

\[ R_s = 2R'_g, \quad R_i = 2R'_i, \quad R_p = 2R'_p, \quad C = C'/2 \]

impedance Z_t can be expressed in a similar form as Eq. (1):

\[ Z_t = (2R'_g + 2R'_i) + \frac{2R'_p}{1 + \omega C' R'_p} = (R_s + R_i) + \frac{R_p}{1 + \omega C' R'_p} \]

The substitution of each element shows that the capacitance (C), which determines the measurement time in the conventional polarization method and A.C. impedance method, is halved. In the present technique, the polarization resistance (R_p) is substituted by twice the polarization resistance on one side (R'_p). The radius to the frequency expressing the peak of the semicircle represents the actual polarization resistance (R_p).

In other words, due to the halved capacitance to be considered and doubled polarization resistance, the frequency that expresses the peak of the semicircle of a Nyquist plot is quadrupled, thereby significantly shortening the measurement time. This is not only experimentally verified but also theoretically proven. It should be noted that the area of reinforcement relevant to the evaluation of polarization resistance is also halved.

In this case, R_s=concrete resistance in the center (Ω), R_i= and R_{st}=concrete resistance in the left and right (Ω), R_g=geometric distribution resistance (Ω), R_g=concrete homogeneity resistance (Ω), R_p=polarization resistance (Ω), and C=capacitance of an electric double layer (μF).

3. Estimation of Concrete Resistivity (ρ_c)

For a corrosion assessment by using a completely nondestructive technique, the information on concrete including the medium between measuring electrodes and steel reinforcement is essential to analyze an equivalent circuit model. Since concrete resistivity indicates the corrosion environment of reinforcement, it is also used as information for the judgment of the corrosion evaluation. Accurate grasping of concrete therefore enhances the reliability of evaluation. For this purpose, it is most desirable to measure concrete directly above the reinforcement under analysis to collect information on concrete around the reinforcement.

In this study, information on concrete is collected using a resistivity estimation model as expressed in Eq. (7). This equation is proposed for estimating the resistivity when a circumferential system with a resistivity of ρ_s exists directly below a semi-infinite isotropic homogeneous medium with a resistivity of ρ_i. The unknown values of the resistivity of concrete (ρ_{c,concrete}) and resistivity of reinforcement
(\rho_{\text{steel}}) are estimated using the known values of the concrete cover depth for the reinforcement, reinforcing bar diameter, and electrode intervals. The estimation is conducted by the minimal error method based on measurements at three or more electrode intervals arranged in parallel to the reinforcement, with the measurement line directly above the reinforcement being in the center. High frequency currents, which eliminate the effect of the boundary impedance between concrete and reinforcement, are used for this measurement, as the effect of reinforcement should be excluded.

\[ V_i = \frac{\rho_1 \cdot I}{\pi a} \left[ \frac{1}{2} + \sum_{n=1}^{\infty} \left[ \frac{K_n \prod_{n=1}^{\infty} \frac{Q_n}{K_n}}{(1 + H_n)^{1/2} - \frac{1}{(4 + H_n)^{1/2}}} \right] \right] \]

\[ + \left[ \prod_{n=1}^{\infty} \frac{Q_n}{K_n} \right] \left[ \frac{1}{(1 + G_n)^{1/2} - \frac{1}{(4 + G_n)^{1/2}}} \right] \]

\[ \text{in this regard,} \]

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

\[ Q_n = \frac{k_n (\rho_2 - \rho_1)}{\sqrt{k_n \rho_2 + \rho_1}} \]

\[ H_n = \frac{d + r(1 - k_n)}{a} \]

\[ G_n = \frac{2nd}{a} \]

where \( V_i \) = apparent potential difference (V)

\( I \) = input current (mA)

\( \rho_1 \) = resistivity of concrete (\( \Omega \cdot m \))

\( \rho_2 \) = resistivity of reinforcement (\( \Omega \cdot m \))

\( d \) = cover depth (m)

\( r \) = reinforcement radius (m)

\( a \) = electrode interval (m)

4. Formulation of a Corrosion Evaluation System by a Completely Nondestructive Method

The main purpose of this study is to develop a completely nondestructive technique for corrosion evaluation by proposing a system comprising an equivalent circuit model and resistivity model that relieves operators from the conventional trouble of chipping cover concrete to determine the polarization resistance and corrosion rate, which serve as indices to corrosion. Figure 5 shows the flow of the corrosion evaluation system proposed in this study.

4.1. Concrete Resistance (\( R_c \) [\( \Omega \)])

For corrosion evaluation by an equivalent circuit, it is necessary first to determine the concrete resistance in the center (\( R_c \), hereafter referred to as “concrete resistance”). The concrete resistance (\( R_c \)) is a path of electric current without passing reinforcement, being subject to the effects of various factors including the resistivity of concrete, which is a physical property of concrete, and geometrical factors, such as depth of concrete cover for reinforcement, reinforcement diameter, and electrode intervals. An optimum value of concrete resistance should be determined to carry out precise corrosion evaluation. However, it was determined in this study by substituting the concrete resistivity (\( \rho_c \)) determined from the model for estimating resistivity into Eq. (12), as the main purpose of this study is to formulate a system for corrosion evaluation.

\[ R_c = \rho_c/(2\pi a) \]

where \( R_c \) = resistivity of concrete (\( \Omega \))

\( \rho_c \) = resistivity of concrete (\( \Omega \cdot m \))

\( a \) = electrode interval (m)

4.2. Geometric Distribution Resistance (\( R_d \) [\( \Omega \)])

It is calculated by determining the voltage value (\( V_a \)) under the same geometrical measurement conditions from the resistivity model of Eq. (7) using the estimated resistivity of concrete (\( \rho_c \)) and the resistivity of reinforcement (\( \rho_r \)), which is assumed to be 0 \( \Omega \cdot m \), and calculating from the relations with the concrete resistance (\( R_c \)). At this time, it is assumed to be unaffected by the boundary impedance in the equivalent circuit (this impedance is assumed to be 0 \( \Omega \)).

4.3. Concrete Homogeneity Resistance (\( R_h \) [\( \Omega \)])

This is determined by calculating the difference between the theoretical average from the resistivity model of Eq. (7) and the measured value for each electrode interval. Thus, different concrete regions covered by different electrode intervals provide the information on the state of resistivity within concrete.

Therefore, when this resistance is close to zero, the distribution of concrete resistivity is homogeneous along the depth. When it is more positive or more negative, the resistivity within concrete is higher or lower, respectively, than the average of the theoretical resistivity. A wider electrode interval expresses the state of a deeper region of concrete.

It is calculated from the relationship between the above-
mentioned concrete resistance \( (R_p) \) and geometric distribution resistance \( (R_g) \) using the voltage values obtained with a high frequency current source for each electrode interval. However, this is assumed to be unaffected by polarization resistance \( (R_p) \) and static capacitance \( (C) \) in the equivalent circuit.

4.4. Polarization Resistance \( (R_p) \) [kΩ·cm\(^2\)]

Since the magnitude of this resistance is assumed to be the radius of the semicircle in a Nyquist plot, the frequency at the peak of the semicircle is measured by frequency sweeping, and the voltage value for the frequency is determined with respect to the relations in the equivalent circuit.

4.5. Static Capacitance of Electric Double Layer \( (C) \) [μF]

Since the capacitance of the electric double layer \( (C) \) on the boundary between concrete and reinforcement shows a frequency dependency, it is a factor that permits a complex analysis for the corrosion phenomenon in a wide range. Though this is known to increase as corrosion proceeds,\(^8\) it is not discussed in this study, as this study mainly deals with corrosion evaluation based on polarization resistance.

4.6. Corrosion Current Density \( (I_{corr}) \)

Corrosion current density \( (I_{corr}) \), which is assumed to be related to polarization resistance \( (R_p) \) as given in the Stern–Geary equation (Eq. (13)) with a proportionality coefficient, \( k \), is used for the prediction of instantaneous corrosion deterioration of reinforcement.

\[
I_{corr} = k/R_p \quad \text{......................(13)}
\]

where \( I_{corr} \) = corrosion current density (μA/cm\(^2\))
\( k \) = proportionality coefficient (V)
\( R_p \) = polarization resistance (Ω/cm\(^2\))

From among the values of proportionality coefficient \( k \) proposed from experiments by Andrade et al.\(^{9)} \) \( (k=0.026 \text{ V in a state of active corrosion and } k=0.052 \text{ V in a passive state}) \), \( k=0.026 \text{ V in a corrosive state} \) was adopted in this study for calculating the corrosion rate in consideration of the effect of chloride included in mortar and forced corrosion deterioration by electrolytic corrosion.

5. Outline of Experiment

5.1. Specimen Fabrication

Figure 6 shows the shape and dimensions of mortar specimens. Mortar was produced using normal portland cement and sand at a ratio of 1 : 2 with a water–cement ratio \( (W/C) \) of 60%, with 3 kg/m\(^3\) of chloride ions \( (\text{Cl}^-) \) being contained, and placed in self-made molds 100×100×400 mm in size, having holes at both ends to fix longitudinal reinforcing steel so that the cover depth would be 30 mm in all specimens.

Reinforcing steel was round bars 13 mm in diameter, which was cut to 410 mm and immersed in a 10% aqueous solution of diammonium citrate for two days to remove the mill scale. The end 35 mm portions on both sides of reinforcing bars were coated with epoxy, so as to be protected from external factors, after connecting leads for inducing electrolytic corrosion and measuring half-cell potential.

When fabricated specimens, the steel surfaces to be exposed to mortar were cleaned with acetone immediately before being fixed to the molds and embedded in mortar. Specimens demolded over 1 d after casting were cured in water at 20°C for 45 d in order to be enough moisture to continue the hydration of cement. Before measurement, specimens were withdrawn from water and coated with epoxy on the four sides to minimize electric leakage from the bars and moisture evaporation from mortar. Also, after sufficiently drying these sides, specimens were subjected to water curing again for 2 d to stabilize their moisture content.

5.2. Levels of Specimens by Electrolytic Corrosion

The state of corrosion of a specimen, which forms levels of the experiment, was adjusted by forcibly polarized reinforcement in mortar by electrolytic corrosion. The method of inducing electrolytic corrosion is as follows: In order to polarize the reinforcement in mortar serving as the anode from a copper plate serving as the cathode as shown in Fig. 7, a pool for containing a 3% aqueous solution of sodium chloride was placed on the top surface of each specimen and filled with the solution so that the copper plate can be submerged to form an electrolytic corrosion circuit. Also, the bottom of each specimen in the container was immersed in the same solution located on the top of the specimen as shown in Fig. 7. The solution was applied to a height of 2 cm from the bottom in consideration for the position of reinforcement and that stabilized the \( \text{Cl}^- \) migration into the specimen and the moisture content of the specimen.

In this test, an anodic corrosion density of 0.72 mA/cm\(^2\) was assumed at the boundary of reinforcement by electrolytic corrosion, which is higher than the normally assumed corrosion current density. This anodic corrosion density level equal to that employed in the preliminary tests on the efficiency of electrolytic corrosion was adopted for each corrosion level, as these preliminary tests revealed that the actual corrosion loss did not follow Faraday’s law, being lower than the expected loss.

Table 1 gives the assumed corrosion loss specified for each specimen. Electric current was applied to each specimen using a constant current generator to the specified assumed corrosion loss level in 0.25% steps.

Specimens A1-1 and A1-2 and all reference specimens A2 were connected in series as shown in Fig. 7 so that the same amount of anodic current would simultaneously flow.
through the specimens. Reference specimens were fabricated eight specimens including A2-1 to grasp indirectly the corrosion processes of A1-1 and A1-2 because it is difficult to directly verify the corrosion losses for these two specimens in every corrosive states.

For A1-1 and A1-2, electrolytic corrosion and measurement were repeated until cracking occurred in the specimens, in order to grasp the changes in the polarization resistance as corrosion proceeded. Reference specimens were used to measure the actual corrosion losses by removing reinforcement from the specimens at each assumed corrosion level.

Reinforcing bars were removed from reference specimens reaching the assumed corrosion level and immersed in a 10% aqueous solution of diammonium citrate for 2 d for derusting. The weight of reinforcement after corrosion was measured using an electronic balance measurable to 0.01 g to calculate the corrosion loss with respect to the weight of the 340 mm zone exposed to mortar by Eq. (14).

$$\Delta W = \frac{W_0 - W}{W_0} \times 100 \quad \text{.................(14)}$$

where $\Delta W =$ mass loss (%), $W_0 =$ initial mass of reinforcement (g), $W =$ mass of reinforcement after derusting (g).

5.3. Measurement Procedure

Figure 8 shows the state of connection between the measuring device controlling a series of operations related to measurement and logging and the electrodes directly above the reinforcement. A conductive gel with a resistivity of $8.3 \times 10^{-6} \ \Omega \cdot \text{m}$ was applied in circles 3 mm in diameter to the measuring surface to increase the conductivity between the measuring electrodes and the mortar surface. Copper wire 1 mm in diameter was placed on the gel spots as electrodes to form a circuit.

Specimens were removed from the water, with the water being wiped off from the measuring surface, and left to stand in a natural corrosion condition for approximately 1 h before measurement, excepting the specimens retaining the initial sound level without electrolytic corrosion. Electrodes were then placed on the measuring surface at the points along the longitudinal line directly above the reinforcement, while keeping the longitudinal center of the specimen, following the procedure of the corrosion evaluation system shown in Fig. 5. Measurement of the response voltage with a 1 mA sinusoidal current was continued while sweeping the frequency from 0.1 to 1 000 Hz and changing the intervals of electrodes arranged according to the Wenner method. A 5 kHz low pass filter was set for the input and output signals to reduce the effect of noise.

6. Test Results

6.1. Half-cell Potential

The half-cell potential of specimens A1-1, A1-2, and reference specimens (RE) for each electrolytic corrosion level was measured to monitor the state of corrosion in accordance with ASTM C 876.

As shown in Fig. 9, the half-cell potential becomes more negative than the potential of 350 mV (vs. CSE), which is regarded as a level with a corrosion probability of 90% in ASTM C 876, as the assumed corrosion loss increases from the sound state of zero to 0.25%. It is therefore judged that corrosion has occurred in the embedded steel due to the electrolytic operation. No marked change occurs until an assumed corrosion loss of 0.75%. Whereas the potential of reference specimens A2-4 and A2-5 levels off at around $-500 \ \text{mV (vs. CSE)}$ with an assumed corrosion loss of 1.0% and 1.25%, that of specimens A1-1 and A1-2 rapidly becomes more negative as the assumed corrosion loss increases from 0.75 to 1.0%. This may be because specimens A1-1 and A1-2 were subjected to repeated measurement, coming into contact with air more frequently than other specimens, and therefore the corrosion environment became severer for these specimens.

6.2. Corrosion Loss

In this study, the state of corrosion of each specimen was uniformly controlled by electrolytic corrosion to examine the changes in the polarization resistance as corrosion proceeds. Since surface cracking began to appear with an assumed corrosion loss of approximately 1.25% in specimens A1-1 and A1-2 as shown in Fig. 10, the current was termi-

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

| Specimen | Assumed corrosion loss |
|----------|------------------------|
| A1-1     | Point of cracking      |
| A1-2     |                        |
| A2-1     | 0.25%                  |
| A2-2     | 0.5%                   |
| A2-3     | 0.75%                  |
| A2-4     | 1.0%                   |
| A2-5     | 1.25%                  |
| Other    | Each of the assumed level |

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nated immediately after confirming cracking to discontinue electrolytic corrosion. At this time, no crack was observed in specimen A2-5, a reference specimen.

As a result of the measurement of recovered reinforcement, the actual corrosion losses were small compared to that of the assumed level and that represented cracks for the smaller value than the results measured for the corrosion loss, 0.8–1.8%, at the crack. Although the corrosion losses at the crack can be varied by the influences of the cover thickness, strength, and porosity of concrete, cracks generally occurred at such corrosion losses more than 2–3%. However, the corrosion loss increased in small steps as shown in Fig. 11. Note that the actual corrosion loss at an assumed corrosion loss of 1.25% is the average of three specimens, A1-1, A1-2, and A2-5.

6.3. Complex Apparent Resistivity

Figures 12(a)–12(f) shows the measured complex apparent resistivity of A1-1 and A1-2 at different corrosion stages with an electrode interval of 4 cm. In the high frequency region, the complex resistivity generally increases as the assumed corrosion level increases, presumably because electrolytic corrosion caused the resistivity of specimens near the surfaces to increase along with reinforcement corrosion. The causes of this phenomenon should be investigated in the future.

Though the apparent resistivity is strongly affected by the polarization resistance in the low frequency region, the effect continues to decrease as corrosion proceeds until cracking, finally being nullified when cracking occurs in the measurement surface. This may be because the flow of current took a path other than the assumed equivalent circuit when cracking occurred.

The phase difference also shows strong effects in the low frequency region, but the effects on both specimens decrease as corrosion proceeds. If the capacitance is assumed to increase as corrosion proceeds, then the frequency for the maximum phase difference should shift toward a lower level. However, the frequency for the maximum phase difference shifts toward a higher level, presumably because the reduction in the polarization resistance is relatively greater than the increase in the capacitance. After cracking, the phase difference disappears for a similar reason as the apparent resistivity.

In a Nyquist plot on real and imaginary axes expressing the result of complex analysis, the frequency for the peak of semicircle is examined to determine the polarization resistance. In the present technique, the peaks are found at a frequency region higher than the 0.01 Hz band by conventional methods. In other words, these tests have proven that this technique shortens the measurement time as stated above in Sec. 2 (Assumption of an Equivalent Circuit Model). While the semicircle of the Nyquist plot becomes smaller as corrosion proceeds, its radius scarcely changes until cracking. This can be attributed to the fact that the corrosion concentrated on a limited area of reinforcement,
as the anodic corrosion surface faced the top surface of mortar, and that the resulting capacitance scarcely changed.

Though the effect of the electrode intervals is not discussed in this paper, the amount of current flowing through the boundary between mortar and reinforcement became relatively greater compared with the amount of current flowing to concrete resistance ($R_c$) as the electrode intervals increased. The effect of boundary impedance also increased. It is therefore considered, when diagnosing using this technique, that ensuring an adequate electrode intervals is a key factor for enhancing the accuracy of diagnosis.

7. Corrosion Evaluation by Completely Nondestructive Technique

7.1. Concrete Resistance ($R_c$)

Figure 13(a) shows the concrete resistance ($R_c$) determined from Eq. (12) using the concrete resistivity ($\rho_c$) estimated by the resistivity model expressed by Eq. (7). As stated above regarding the results of complex apparent resistivity testing, the small increases in the concrete resistance express the effect of the increase in the concrete resistivity ($\rho_c$) on the surface side as it is. Further investigation is required to adequately calculate this resistance for a more accurate determination of polarization resistance by this evaluation system.

7.2. Geometric Distribution Resistance ($R_g$)

Since the geometric distribution resistance is subject to the effect of concrete resistivity ($\rho_c$), it shows similar tendencies as the concrete resistance ($R_c$) as shown in Fig. 13(b). This resistance relatively decreases as the cover depth decreases, as the electrode interval increases, and as the bar diameter increases. In other words, geometric distribution resistance is a resistance expressing the difficulty for electric current to reach reinforcement.

7.3. Concrete Homogeneity Resistance ($R_i$)

Figure 13(c) shows the changes in the concrete homogeneity resistance ($R_i$) as corrosion proceeds with electrode intervals of 4 cm. In specimens A1-1 and A1-2, the resistance is found to become significantly more negative as the test proceeds. This means that the resistivity within concrete is lower than that near the surface. In other words, this explains the judgment that the above-mentioned increases in the concrete resistivity ($\rho_c$) is due to the increases in the resistivity near the mortar surface. Though the results of specimens RE (A2-1 to A2-5) scatter, they shift toward the negative side, suggesting that their internal resistivities are lower than the average. The resistivity distribution within concrete can therefore be diagnosed completely nondestructively by this technique.

7.4. Polarization Resistance ($R_p$)

Figure 13(d) shows the polarization resistance ($R_p$) calculated by the corrosion evaluation system proposed in this study. This figure clearly shows a decreasing tendency as corrosion proceeds, with all corrosion degrees indicating values not more than 100 k$\Omega$·cm$^2$ excepting the sound state of specimen A1-1 with no corrosion loss. These polarization resistance values all fall in the range ($R_p < 250$ k$\Omega$·cm$^2$) proposed by Building Research Establishment, as a judgment criterion for corrosion. The completely nondestructive technique proposed in this study is therefore proven to be capable of diagnosing corrosion deterioration in reinforced concrete structures.

The polarization resistance of specimens A1-1 and A1-2 is close to zero at assumed corrosion losses of 1.0% and 1.25%. This can be attributed to changes in the current path.
due to possible expansion cracks caused by corrosion products in and out of reinforcement.

7.5. Corrosion Current Density ($i_{corr}$)

As shown in Fig. 13(e), the corrosion current density ($i_{corr}$) tends to increase as corrosion proceeds in contrast to polarization resistance ($R_p$). Since the values of A1-1 and A1-2 soar at assumed corrosion losses of 1.0% and 1.25% where the polarization resistance is close to zero, these are not shown in Fig. 13(e).

8. Summary

In this study, authors attempted a formulation of the corrosion evaluation system for evaluating corrosion deterioration generated in reinforced concrete structures using a completely nondestructive method. An equivalent circuit was proposed to this formulation by considering a resistivity measurement method. Also, a resistivity estimation model was introduced to obtain the information of concrete for analyzing the equivalent circuit. This system for evaluating such corrosion was verified by corrosion loss tests for its applicability to laboratory studies and field diagnoses. The results and information obtained from this study are summarized as follows:

1) An equivalent circuit was assumed in consideration of the characteristics of the resistivity measurement method in which the measurement range is determined by the outer current electrodes. The theoretical grounds for the benefits of this method, such as shortened measurement time and simplicity of corrosion evaluation, were presented, thereby clarifying the adequacy of this method.

2) In order to grasp the effects of concrete, which are essential for corrosion evaluation of steel reinforcement by the completely nondestructive technique, a resistivity model was employed in this study to estimate the resistivity of concrete surrounding specific reinforcement and calculate the polarization resistance in the equivalent circuit. This was proven usable as a key means for the study and diagnosis of corrosion. It is considered necessary to improve the method of estimating the resistance of concrete, the medium for diagnosis, so as to enhance the accuracy of corrosion evaluation.

3) In this study, the authors formulated a corrosion evaluation system and carried out corrosion evaluation in regard to actual corrosion tests based on the system, to investigate the applicability of the system. The calculation of concrete resistance, geometric distribution resistance, concrete homogeneity resistance, and polarization resistance was also attempted.

As a result, concrete homogeneity resistance was found to be particularly usable as an index enabling the prediction of the internal distribution condition of concrete resistivity. This resistance expresses the resistivity of a given region of concrete, which depends on the electrode intervals, relative to the average concrete resistivity estimated from the resistivity model.

Evaluation by polarization resistance and corrosion current density based on polarization resistance expresses well the tendencies associated with the development of corrosion, proving that corrosion evaluation is feasible by the present technique. This technique is expected to provide key information for laboratory research into reinforcement corrosion and field prediction of the service life of reinforced concrete structures.

Based on this study, the authors intend to continue investigation in more detail to develop a completely nondestructive corrosion technique applicable to various situations of reinforced concrete structures.

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