Study of Reinforced Concrete Corrosion Using Impedance Measurements
Objective

To develop a new non-destructive method that uses a multielectrode electrical resistivity array to measure the complex impedance along the surface of a concrete structure in order to determine the position of the reinforcing bars and their corrosion state.
Challenges

1) It should be able to locate the reinforcing bar, and be able to localize the measurement to identify the location of a bar undergoing corrosion.

2) It must make the measurement from the surface of concrete.

3) It must measure the electrical resistivity of the concrete itself.

4) It must measure the properties of the interface.

5) It must be simple to use and require a minimum of data processing.
The Method
The Proof of Concept
Cast a large concrete block with different bars
Gold bar
Casting
Block
Rebars were located and their surface identified.

![Graph showing phase vs. frequency for different rebar conditions: No.1, As received; No.2, Clean; No.3, Painted; No.4, Gold-coated.](image)
Test set-up
Results

The graph shows the resistivity modulus (Ω.m) as a function of frequency (Hz). The graph includes different腐蚀 currents: Free corrosion, 0.05 μA/cm², 1.0 μA/cm², 5.0 μA/cm², and 10 μA/cm².

The data indicates a decrease in resistivity modulus with increasing frequency for all corrosion currents, with the Free corrosion case showing the least change in resistivity modulus.
Specimen A2
Pseudosection location $\rho_{2,1}$

- Free corrosion
- $0.05 \mu A/cm^2$
- $1.0 \mu A/cm^2$
- $5.0 \mu A/cm^2$
- $10 \mu A/cm^2$
Results

![Graph showing the results of corrosion measurements for different conditions and frequencies.](image)

- **Free corrosion**
- **0.05 µA/cm²**
- **1.0 µA/cm²**
- **5.0 µA/cm²**
- **10 µA/cm²**

- **Frequencies:** 0.01 Hz, 0.1 Hz
Looks good but life is never that easy...

... to become quantitative needs to solve the inverse problem
Model

Input $I$ for $x = 0$

Prospecting of $V$

$2r_0$

Concrete, $\rho_1$

Rebar, $\rho_0$

Interface, $z_{interface}$

Plane $yz$ for $x = 0$

Plane $xy$ for $z = 0$
Fundamental equations

Poisson equation:

\[
\frac{1}{r} \frac{\partial}{\partial r} \left( \frac{\partial V(\mathbf{r})}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 V(\mathbf{r})}{\partial \theta^2} + \frac{\partial^2 V(\mathbf{r})}{\partial z^2} = \frac{I}{4\pi} \rho_1 \delta(\mathbf{r} - \mathbf{r}_s)
\]

\[
V_0(\mathbf{r},z) = \frac{I}{2\pi^2} \sum_{m=0}^{\infty} \left[ \int_0^{\infty} A_m(u)I_m(\mathbf{r}u)\cos(uz)du \right] \cos(m(\theta - \theta_0))
\]

\[
V_1(\mathbf{r},z) = V^p(\mathbf{r},z) + \frac{I}{2\pi^2} \sum_{m=0}^{\infty} \left[ \int_0^{\infty} B_m(u)K_m(\mathbf{r}u)\cos(uz)du \right] \cos(m(\theta - \theta_0))
\]
Coefficients

\[
B_m(u) = \frac{\sigma_0 \left[ (2 - \delta_0) K_m(u_r) I_m(u_{r_0}) \right] \left[ u \times I_{m-1}(u_{r_0}) - \frac{m \times I_m(u_{r_0})}{r_0} \right]}{\sigma_i \left[ I_m(u_{r_0}) + Z_{\text{interface}} \sigma_i \left( u I_{m-1}(u_{r_0}) - \frac{m \times I_m(u_{r_0})}{r_0} \right) \right]} - (2 - \delta_0) K_m(u_r) \left[ u I_{m-1}(u_{r_0}) - \frac{m \times I_m(u_{r_0})}{r} \right] \left[ u K_{m-1}(u_{r_0}) - \frac{m K_m(u_{r_0})}{r} \right]
\]

\[
A_m(u) = \frac{(2 - \delta_0) K_m(u_r) I_m(u_{r_0}) + B_m(u) K_m(u_{r_0})}{I_m(u_{r_0}) + Z_{\text{interface}} \sigma_i \left( u I_{m-1}(u_{r_0}) - \frac{m \times I_m(u_{r_0})}{r_0} \right)}
\]

Yes, it does get more complicated than this because we need to solve for the half-space (please see paper for details)
Once model is done we can run simulations

Interface impedance simulated by the simple electrical circuit

\[ R_e = 0.0005 \ \Omega.m^2 \]
\[ C_d = 0.15 F/m^2 \]
\[ R_p = 2.5 \ \Omega.m^2 \]

\[ R_p = 25 \ \Omega.m^2 \]
1. Geometry effect

Electrode array: Wenner

Concrete cover $D$ / rebar radius $r_0$

- $D/r_0 = 3$
- $D/r_0 = 2$
- $D/r_0 = 1$

$r_0 = 0.0127 \text{ m (1/2 in.)}$

$\rho_1 = 100 \text{ \Omega.m (concrete)}$

$\rho_0 = 0.01 \text{ \Omega.m (rebar)}$
2. Apparent resistivity response with corrosion rate

Concrete, rebar, and geometric properties

- $\rho_{\text{concrete}} = 50 \ \Omega\cdot m$
- $\rho_{\text{rebar}} = 10^{-6} \ \Omega\cdot m$
- $D = 0.0254 \ m$ (1 in.)
- $r_0 = 0.00635 (1/4 \ in.)$

$R_p = 2.5 \ \Omega\cdot m^2$
- $R_p = 25 \ \Omega\cdot m^2$

Interface impedance simulated by the simple electrical circuit:
- $R_e = 0.0005 \ \Omega\cdot m^2$
- $C_d = 0.15 \ F/m^2$

3. Geometry effect on corrosion measurement

Concrete, rebar, and geometric properties

\[ \rho_{\text{concrete}} = 50 \, \Omega \cdot m \quad \rho_{\text{rebar}} = 10^{-6} \, \Omega \cdot m \]

Interface impedance

\[ R_p = 2.5 \, \Omega \cdot m^2, \quad C_d = 0.15 \, \text{F/m}^2 \]

\[ r_0 = 0.00635 \, \text{m} (0.25 \, \text{in.}) \]

\[ D = 0.0254 \, \text{m} (1 \, \text{in.}) \]

\[ D = 0.0381 \, \text{m} (1.5 \, \text{in.}) \]

Frequency (Hz)
Conclusions

- The Surface Measurement Method accurately detects the different corrosion states of embedded reinforcing bars in concrete structures. This method is applied on the structure surface, with no need to connect with the reinforcement. In addition, it localizes the measurement to a confined segment of the rebar beneath the electrode array.
Conclusions

- The measured resistivity spectra distinguish various corrosion rates and various corrosion extents. The decreased resistivity modulus and peak phase angle can be used to characterize how rapidly the reinforcing bar is corroding, and the peak phase angle shift to a smaller frequency indicates to what extent the reinforcing bar has corroded.
Conclusions

- The analytical solution is obtained to the surface-based measurement of rebar corrosion in concrete.
- Both the analytical and experimental study confirmed the capability and feasibility of the new method as a prospective quick, convenient, and quantitative solution to corrosion detection.
References


