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On-site transient analysis for the corrosion assessment of reinforced concrete

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Abstract

A range of methods exist to assess the condition of steel reinforcement in concrete. The analysis of the transient response to a small perturbation has been employed successfully in laboratories to assess corrosion. This work examines a simplified method for the application of transient analysis to in-situ reinforced concrete structures. The complex analysis has been simplified and undertaken with the use of common spreadsheet packages. The results illustrate that transient response analysis is a viable technique for use on site and appears to provide a more accurate representation of steel corrosion current densities at very low values than polarisation resistance.

Keywords: Concrete (A), steel reinforced concrete (A), EIS (B), polarization (B), cathodic protection (C).

Introduction

The study outlines a trial of transient response analysis on full-scale motorway bridge structures to obtain information concerning the steel-concrete interface and is part of a larger study to assess the long-term sustained benefits offered by Impressed Current Cathodic Protection (ICCP) after the interruption of the protective current [1]. These structures had previously been protected for 5 to 16 years by an ICCP system prior to the start of the study. The protective current was interrupted, in order to assess the long-term benefits provided by ICCP after it has been turned off. This paper develops and examines a simplified approach for the on-site use of transient response analysis and
discusses the potential advantages of the technique as a tool for the assessment of the corrosion condition of steel in reinforced concrete structures.

Theoretical background

Impedance has been used previously to obtain corrosion information regarding the steel-concrete interface \([2-3]\). To obtain this information, data is required at very low frequencies (mHz – μHz) \([2-5]\). The conventional method of obtaining impedance is to subject the specimen to a cyclic perturbation at the frequency of interest and analyse the response \([2, 6]\). However, at very low frequencies it is preferable to subject the specimen to a perturbation and analyse its response resulting from the perturbation \([7-10]\).

The steel-concrete system can be described in the form of an electrical circuit. A common and simple approach is the use of the Randle’s circuit (Figure 1a). This analysis characterises the steel-concrete interface with a polarisation resistance \((R_p)\), interfacial capacitance \((C)\) and electrolyte resistance \((R_e)\). \(R_p\) can be directly associated with the steel corrosion current density \((I_{corr})\) \([11-12]\). The validity of the simple Randle’s circuit to adequately represent the steel-concrete interface is still subject to debate. Impedance data may appear to produce a distorted or flattened semi-circle and at high frequencies a second semi-circle may appear \([7]\).

A number of alternative electrical circuits have also been proposed incorporating additional components in order to obtain a better fitting of the experimental data, as shown in Figure 1b, 1c and 1d \([13-16]\). These additional components improve the fit of the data because each component represents an additional variable that may be adjusted to improve the fit.

Impedance data may be presented in a Bode plot of the response function of a linear-time invariant system versus frequency or a Nyquist plot as a parametric plot of a transfer function, with the latter most commonly used \([17]\). The shape of the impedance plane on a Nyquist plot gives an indication regarding the accuracy of the model. A near perfect semi-circle will indicate that the impedance response corresponds to a single activation-controlled process (Figure 1a), a depressed semi-circle will indicate a need for parallel components (Figures 1b and 1c) model and multiple semi-circles in general indicates a series of components (Figure 1d) \([17]\).
In this work the simplified Randle’s circuit has been applied due to its simplicity for data analysis \[7, 15\]. This approach provides an estimate of the corrosion condition in critical sections of the structure and is particularly suitable for use on full-scale site structures due to its simplicity. Feliu et al. \[18\] also support the use of a simplified abstract representation of the system in order to interpret its fundamental properties as opposed to a more accurate but significantly more complex circuit model.

Transient response analysis is used to overcome the complexity of the frequency response analysis and simplified for use on site. Transient analysis is the analysis of the response of an electrode after the application of a short pulse over a period of time.

**Transient data analysis**

Laplace transformation is used to convert data on the time domain to data on the frequency domain. This transformation may be expressed as \[19\]:

\[
\bar{Z} = \frac{\overline{V}}{I} \quad \text{(Eq. 1)}
\]

The Laplace transformations of \( \overline{V} \) and \( \overline{I} \) can be written as \[3\]:

\[
\overline{V} = a + jb = \int_{0}^{\infty} \Delta E(t)\cos(\omega t)\,dt - j\int_{0}^{\infty} \Delta E(t)\sin(\omega t)\,dt \quad \text{(Eq. 2)}
\]

\[
\overline{I} = a + jb = \int_{0}^{\infty} I(t)\cos(\omega t)\,dt - j\int_{0}^{\infty} I(t)\sin(\omega t)\,dt \quad \text{(Eq. 3)}
\]

where \( \Delta E \) is the difference in potential, \( I \) is the current, \( t \) is the time and \( \omega \) is the range of angular frequencies of interest.

When the highest frequency of interest has a period which is much greater than the period of the pulse \( \left( \frac{1}{\omega} >> T \right) \) and for times less than the period of pulse \( (I(t) \neq 0) \) then \( \sin(\omega t) \approx 0 \), \( \cos(\omega t) \approx 1 \) and Equation (3) becomes:

\[
\overline{I} = \int_{0}^{\infty} I(t)\,dt = Q \quad \text{(Eq. 4)}
\]

where \( \omega' \) is the highest frequency of interest, \( T \) is the period of the pulse and \( Q \) is the charge.
Under these conditions the Laplace transformation of the current perturbation will be the charge.

Equations 1 and 2 can be solved using standard spreadsheet packages and is illustrated as follows:

i. $\Delta E$ and $I$ are measured from the transient data obtained on site. A typical representation is given by Figure 2a. The data is a set of discrete points.

ii. The voltage transformation from Equation (2) is a function of the angular frequency ($\omega$), in the range of frequencies of interest. Figure 2b illustrates a typical example of the contents of the real integral of Equation (2) at a selected value of $\omega = 0.04$Hz.

iii. Figure 2c illustrates a typical example of the contents of the imaginary integral of Equation (2) at a selected value of $\omega = 0.04$Hz.

iv. The real and imaginary integrals can be calculated simply by the respective areas under the curves in Figures 2b and 2c. For equally spaced points, it is calculated as the sum of the points multiplied by the spacing (seconds) between the points.

v. The real and imaginary parts of equation (2) can then be divided individually by the charge to obtain the impedance for this particular angular frequency.

vi. This gives a point on the Nyquist plot at a selected value $\omega = 0.04$Hz. The real integral divided by the charge provides the x-axis value and the imaginary integral divided by the charge provides the y-axis value (Figure 2d).

vii. The above procedure can be repeated at different angular frequencies ($\omega_x$) in order to obtain the impedance spectrum. The procedure provides a suitably simplified analysis process for use with site data.

For very low frequencies where $\omega \ll 0$ equation (2) may be simplified further as follows:

\[
\bar{V} = \int_0^\infty \Delta E(t) dt \quad \text{(Eq. 5)}
\]

Therefore equation (1) becomes:

\[
\bar{Z} = \frac{\int_0^\infty \Delta E(t) dt}{\int_0^\infty I(t) dt} = R_p \quad \text{(Eq. 6)}
\]
The impedance value of equation (6) is given by the area under the curve of Figure 2a for the potential transient divided by the charge (DC resistance). The low-frequency real axis intercept (highest x-axis value of the semi-circle) represents the polarisation resistance \( R_p \) and electrolyte resistance \( R_e \). The high-frequency real axis intercept (lowest x-axis value of the semi-circle) represents the electrolyte resistance \( R_e \). Applying a short pulse and measuring the potential decay after the pulse has been applied eliminates the effect of \( R_e \) in the measurement process.

The observed peak in the Nyquist plot is the characteristic frequency of the structure from which useful information about the corrosion state of the reinforcement can be obtained. The characteristic frequency of the steel-concrete interface \( f_c \) can be obtained from the following Equation [3]:

\[
f_c = \frac{1}{2\pi R_p C}
\]

(Eq. 7)

The highest frequency is limited by the period of the pulse. The lowest frequency is not limited if we can assume that after the potential has decayed to the rest potential there is no contribution from the remaining area under the transient.

Care must be taken however, as for some models the above assumptions will not be true. In these exceptions, transients should be measured for a period which is longer than the period which is longer than the lowest period of the frequency of interest.

Having obtained impedance information for the steel-concrete interface, it is also possible to calculate the corrosion current density of the section as it is inversely proportional to the polarisation resistance \( R_p \) [5, 11].

\[
I_{corr} = \frac{B}{R_p}
\]

(Eq. 8)

where \( B \) is a constant of the metal/electrolyte system depending on the Tafels constants of the polarisation curves. For steel in concrete and in particular site uses, a value of 26mV is typically used for simplicity [5, 7, 11, 20].
Experimental Procedure

A number of steel-reinforced concrete structures were selected to identify the long-term benefits afforded by ICCP. All the structures had their protective current interrupted for a period of 36 months (since October 2007) in order to evaluate these long-term benefits [1]. A total of 10 structures were selected based on the age of the installed ICCP system, accessibility and chloride levels. All structures selected for this study were protected by ICCP and the anode system comprised a conductive anode coating. The anode systems were from varying anode suppliers and this helped to also assess their relative performance and durability.

Samples for chloride analysis were collected to identify areas of residual risk. The locations of testing were in original un-repaired concrete and the chloride contents are expressed as weight percent of cement and for a depth of 25 to 50 mm where the reinforcement is present (Table 1). From the results it can be observed that there were several locations within the structures where the chloride content at the depth of the reinforcement was sufficiently high to pose a corrosion risk following interruption of the protective current.

Based on the chloride sampling at the depth of reinforcement, 2 locations representative of high corrosion risk for each structure were selected for further monitoring. These locations, of an approximate area of 0.35 m², were cleaned and had the old conductive coating anode removed. Following cleaning, a new conductive coating anode (coloured black) was installed as shown in Figure 3. One Ag/AgCl/0.5 M KCl reference electrode was installed in the middle of each anode segment to assess the steel potential shift.

The existing anode segment acts as a counter electrode and the rest of the anode system acts as a guard ring (Figure 3) to confine a current perturbation of the anode segment to the steel below the anode segment during the corrosion rate measurement process [1].

The technique limits the edge effects of a current perturbation applied from a counter electrode to the concrete structure by also applying current from a guard electrode surrounding the counter electrode. The guard ring method for confinement of the current in a localised area is a popular and successful technique used in laboratory and site applications [7, 21-24]. The method allows corrosion monitoring
of selected localised areas of a large reinforced concrete structure. Minimising edge effects is particularly important when the steel reinforcement is passive.

The full testing arrangement developed is illustrated in Figure 4. Briefly the main elements were the existing power supply enclosure located at ground-level, the existing ICCP enclosure at high-level, the monitored anode segment and a new enclosure at high-level to facilitate the new connections to the system [1]. The current density delivered by the guard electrode was adjusted to be the same as that delivered by the counter electrode.

At each site visit two tests were undertaken on each structure. During the first test, the system received a short charge of approximately 5 seconds, and the potential decay was recorded at 1 second intervals with use of a data logger for a period up to 15 minutes.

The second test involved applying a perturbation to the structure for a longer period of approximately 10 minutes. The data logger was used again to record the polarisation of the structure. The data collected was then used to undertake polarisation resistance analysis.

Analysis

A pattern arose from the potential decay data recorded during the transient response testing: the structures exhibited a relative long potential decay back to their pre-pulse rest potential. This is consistent with data reported by others for passive reinforcement [3, 25-27]. Figure 2a illustrates typical potential decay data. This provides a basis for a criterion for use on site to quickly determine the corrosion state of reinforcement. Steel potentials were measured against a Ag/AgCl/0.5 M KCl reference electrode.

From the analysis of the potential transients a set of data was obtained for each structure in the present study over a period of 31 months. Figure 5 illustrates typical Nyquist plots arising from the analysis of transients obtained from one site visit for all structures. The results illustrate high polarisation resistance ($R_p$) values in the range of 51 to 210 $\Omega$.m$^2$ and very low characteristic frequencies ($f$) in the region 1 to 5 mHz. It can be observed that the associated $I_{corr}$ are very low indicating passive reinforcement. By comparison, linear polarisation resistance analysis calculated the corrosion current density to be 0.03 mA/m$^2$ whereas a corrosion current density of 0.15 mA/m$^2$ was
The data obtained in other studies [28-29] also supports that non-corroding reinforcement will have very low characteristic frequencies and high polarisation resistance values.

Figure 6 plots the associated corrosion current densities based on transient response analysis of all 10 structures as a function of time over a period of 30 months. It can be observed that all the structures retained their passive condition despite several locations having a high residual chloride content. At the same time corrosion current densities were also monitored based on the polarisation resistance testing as part of the previous work [1]. Figure 7 illustrates the results of polarisation resistance testing over a period of 36 months. Both the polarisation resistance and transient analysis data suggest that the steel remains passive.

Looking at the corrosion current densities obtained for structure A3 (Figure 8), it can be observed that transient analysis provided more consistent data than polarisation resistance with regards to the corrosion status of the monitoring locations on the structure. Occasionally, polarisation resistance returned unrealistically low corrosion current densities, something that was observed on other structures too.

Figure 9 compares the results obtained from polarisation resistance and transient response analysis in a histogram. It can be observed that polarisation resistance consistently produced very low corrosion current densities. It is noted that these data are provided with no check on whether the corrosion current densities measured, actually do represent the corrosion rates. This is a set of measurements taken from full scale bridge structures and an assumption is made that the information drawn from the method gives indeed the true corrosion rate.

Table 2 then illustrates typical corrosion current densities for all 10 structures and their calculated interfacial capacitance. It can be seen that corrosion current densities for non-corroding structures are in general associated with high polarisation resistance, low interfacial capacitance and very low characteristic frequencies. Similar findings have been reported by others [3, 29].

Discussion
Impedance information arising from potential transients can produce useful information concerning the corrosion state of steel reinforcement. The results obtained during this study confirm the previously reported findings [1] that there is a low corrosion risk from all structures examined despite 36 months of no protection. Furthermore, the impedance spectra obtained on-site from full-scale reinforced concrete structures are similar to published data obtained on passive specimens in laboratory testing confirming the passive status of the steel reinforcement [3, 26, 30]. The complex analysis required for impedance has been simplified and successfully applied to full-scale site structures and undertaken with common spreadsheet packages.

The data collected from transient response analysis indicated that all structures had a relatively long potential decay of approximately 10 minutes back to their rest potential after the application of a short perturbation. Passive steel reinforcement can be associated with a relative long potential decay (>10 mins) back to its rest potential after the application of a short (<5 s) current pulse. It is postulated that this could be developed into a rapid technique for assessing the corrosion condition of reinforced concrete structures on site and idea also supported by others [27].

Polarisation resistance in general returned more frequently extremely low \( I_{corr} \) values as opposed to transient response analysis. This indicates the possibility that polarisation resistance may under-estimate the corrosion current densities or transient response analysis may over-estimate them. The differences observed may be explained by the size of the data set, polarisation resistance effects and the length of perturbation.

Transient response analysis is based on a large amount of data collected over a specific time period, typically in excess of 300 points, whereas with polarisation resistance the data collected is focused at two points only, i.e. the start and the end of the testing. The larger data set helps reduce scatter, which may be a problem for site data.

Polarisation resistance measurements are obtained while current is applied, whereas for transient response analysis all the data are collected after the current perturbation has been applied and as such they do not include the effects of the resistance of the concrete \( R_o \). Therefore, corrosion current densities through polarisation resistance analysis have to be compensated for IR effects. Furthermore, the perturbation applied during polarisation resistance is over a greater time and of higher average
magnitude than the perturbation for the transient response analysis, which also might affect the
results.

Capacitance of the steel concrete interface was not directly measured as part of this work but it was
calculated based on the characteristic frequency and the polarisation resistance of the structure. The
calculated interfacial capacitance was found to be significantly lower than that reported for active steel
in other studies [3, 29, 31]. It is postulated that the presence of an intact passive oxide film contributes
to this effect.

Conclusions

1) The analysis of transients to obtain information on the corrosion condition of steel in concrete
has been successfully applied to full-scale site structures for the first time. The complex
analysis required for impedance can be simplified and can be undertaken with the use of
common spreadsheet packages. Polarisation resistance which is related to the corrosion
current density is equal to the area under a potential time transient divided by an area under a
current pulse perturbation which was applied to produce the potential transient.

2) Passive steel reinforcement is associated with a relative long potential decay (>10 mins) back
to its rest potential after the application of a short (<5 s) current pulse. It is postulated that this
could be developed in the future into a rapid technique for assessing the corrosion condition of
reinforced concrete structures on site.

3) At low corrosion current densities (up to 2 mA/m²) transient response analysis appears to
provide more accurate data than that obtained from the polarisation resistance analysis.
Possible reasons for this include the analysis of a larger data set to obtain the transient
response, the use of a smaller perturbation and the removal of the concrete resistance.

4) The interfacial capacitance ($C$) calculated from the characteristic frequency of the structures
appears to be lower than that published for corroding structures. It is postulated that the
presence of an intact passive oxide film contributes to this effect.

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**Figure Captions**

Figure 1: Various electrical circuits to simulate the steel concrete interface, (a) Randle’s circuit, (b) modified Randle’s circuit holding two time constants [14], (c) model proposed by Feliu et al. [15], (d) model proposed by John et al. [16].

Figure 2: Graphical representation of the calculations involved in converting transient data into impedance (ω > 0) and resistance (ω = 0).

Figure 3: Guard ring arrangement on a reinforced concrete motorway cross beam

Figure 4: Testing arrangement [1]

Figure 5: Nyquist plots arising from transient analysis for all ten structures

Figure 6: Corrosion current densities from transient response analysis over a period of 30 months

Figure 7: Corrosion current densities from polarisation resistance testing over a period of 36 months

[1]

Figure 8: Corrosion current densities for structure A3 obtained from polarisation resistance testing against transient analysis
Figure 9: Return of results from transient response and polarisation resistance analysis. *(Note: Frequency is dimensionless and the x-axis does not cover equal-interval or numerically consistent divisions of the x axis. The graph should not be read as a quantitative distribution or histogram).*

Tables

| Structure Reference | Year of Installation | Age of structure at testing (years) | Locations with Cl- greater than 1% by weight of cement (at depth of steel) | No of test locations | Locations with Cl- greater than 0.4% by weight of cement (at depth of steel) |
|---------------------|----------------------|-----------------------------------|--------------------------------------------------------------------------|---------------------|--------------------------------------------------------------------------|
| A1                  | 1991                 | 40                                | 2                                                                         | 4                   | 4                                                                         |
| A2                  | 1995                 | 40                                | 2                                                                         | 5                   | 3                                                                         |
| A3                  | 1995                 | 40                                | 2                                                                         | 5                   | 4                                                                         |
| B1                  | 1996                 | 40                                | 3                                                                         | 6                   | 4                                                                         |
| B2                  | 1998                 | 40                                | 1                                                                         | 5                   | 4                                                                         |
| B3                  | 1998                 | 40                                | 2                                                                         | 5                   | 3                                                                         |
| B4                  | 1998                 | 40                                | 2                                                                         | 5                   | 3                                                                         |
| C1                  | 1999                 | 40                                | 0                                                                         | 5                   | 2                                                                         |
| C2                  | 2002                 | 40                                | 0                                                                         | 5                   | 1                                                                         |
| C3                  | 2000                 | 40                                | 0                                                                         | 5                   | 1                                                                         |

Table 1: Details of the 10 structures investigated by Christodoulou et al. 2010 [1].

| Structure Reference | Locations with Cl- greater than 1% by weight of cement | Characteristic Frequency (f) Hz | Polarisation Resistance (R_p) Ω.m^2 | Corrosion Current Density (I_corr) mA/m^2 | Capacitance (C) F/m^2 |
|---------------------|--------------------------------------------------------|---------------------------------|-------------------------------------|-------------------------------------------|------------------------|
| A1                  | 2                                                      | 0.005053                        | 84                                 | 0.31                                      | 0.37                   |
| A2                  | 2                                                      | 0.00171                         | 51                                 | 1.12                                      | 1.42                   |
| A3                  | 2                                                      | 0.0015                          | 152                                | 0.13                                      | 0.70                   |
| B1                  | 3                                                      | 0.0019                          | 69                                 | 1.26                                      | 1.21                   |
| B2                  | 1                                                      | 0.0066                          | 192                                | 0.27                                      | 0.13                   |
| B3                  | 2                                                      | 0.000783                        | 431                                | 0.07                                      | 0.47                   |
| B4                  | 2                                                      | 0.003                           | 112                                | 0.23                                      | 0.47                   |
| C1                  | 0                                                      | 0.00215                         | 209                                | 0.12                                      | 0.35                   |
| C2                  | 0                                                      | 0.0018                          | 477                                | 0.05                                      | 0.19                   |
| C3                  | 0                                                      | 0.001052                        | 179                                | 0.15                                      | 0.85                   |

Table 2: Calculated capacitance and corrosion current densities based on impedance analysis.
$C$: Capacitance  
$R_e$: Electrolyte resistance  
$R_p$: Polarisation resistance  
$a$: Time constant
Figure 2

Step 1 – Calculate $\Delta E$ and $\Delta I$

Step 2 – Select a frequency $\omega_x$ and calculate $\int \Delta E(t) \cos(\omega t) dt$

Integral is sum of areas under the curve.

Step 3 – Calculate $\int \Delta E(t) \sin(\omega t) dt$ for selected frequency $\omega_x$.

Integral is sum of areas under the curve.

Step 4 – Obtain a point on the Nyquist plot:

$$R_p = \frac{\int_{0}^{\infty} \Delta E(t) dt}{\int_{0}^{\infty} \Delta I(t) dt}$$

Figure 2a – Typical Potential Response and Current Perturbation

Figure 2b – Typical real integral solution

Figure 2c – Typical imaginary integral solution

Figure 2d – Typical Nyquist plot of transient analysis
Figure 3

Anode Segment (counter electrode)

Anode (guard electrode)

Reference electrode
Figure 9

(a) Impedance

(b) Polarisation Resistance

Frequency of occurrences vs. Corrosion current density (mA/m²)
1 Highlights
2 • On-site transient analysis of concrete structures for corrosion assessment
3 • ICCP system turned off to investigate its long-term secondary protective effects
4 • The complex analysis can be simplified and undertaken with common spreadsheet packages
5 • Passive steel shows a long potential decay back to its rest potential after a short perturbation
6 • Transient analysis may provide more accurate information than polarisation resistance