

New Rapid Nondestructive Electrical Testing Method for Detecting and Quantifying Steel Corrosion in Saltwater and Clay Soil Using the Vipulanandan Impedance Corrosion Model

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ABSTRACT

In this study, carbon steel corrosion was measured in salt water solutions and moist bentonite clay using the newly developed non-destructive electrical method which can be easily adopted in the field for real-time monitoring and the results were compared to some standard test methods such as weight loss. The average weight loss in 10% salt solution in one year was 1.05% and corrosion rate was 1.54 mm/year. The use of the new nondestructive electrical method was to detect and quantify the surface and bulk corrosion. Tests were performed to first verify the best electrical property that will be highly sensitive and represent the steel corrosion. The findings from this study indicated changes in the newly developed electrical corrosion index for the surface (2D representation) and the resistivity (second order tensor, 3D representation) for the bulk material using the Vipulanandan Corrosion Impedance model. Corrosion development in 30 inches long steel specimens were studied in the 3.5% salt solution (simulating sea water) for 500 days. The surface corrosion was quantified using the new electrical corrosion index parameter, and the change was over 200%. The steel in the bentonite clay for over 600 days showed a surface corrosion of about 40%. The change in the bulk resistivity along the length of the steel specimen was over 40,000 times (4,000,000%) in 3.5% salt solution compared to about 1.05% change in the weight in one year. Hence the electrical resistivity for the bulk material and the corrosion index for the surface corrosion are highly sensing parameters for detecting and quantify the corrosion in the steel.

INTRODUCTION

Steel is used as a construction material both onshore and offshore. In order to improve the maintenance operations and also extend the service life of oil and gas wells, petrochemical plants and supporting infrastructures it is very important to detect and quantify corrosion real-time (Vipulanandan et al. 2002-2021). Corrosion degrades the material by bio-chemical reactions, stress fatigue degradation, temperature cycles with the exposed environments. In addition to daily encounters with this kind of degradation, corrosion causes failures, fire hazards due to pipeline

leakages, plant shutdowns, waste of valuable resources, loss and contamination of product, reduction in productivity and expensive maintenance.

Corrosion of metals alone cost the U.S. economy more than \$300 billion per year, approximately one-third of these could be saved by proper corrosion detection and quantification (Corrosion: Understanding the basics, 2000). NACE has reported that losses due to corrosion are equal to 1-5 % of the country's Gross National Product (GNP) which sums up to several billion dollars. The annual cost of corrosion in the USA oil and gas industry is over \$27 billion and globally \$60 billion. (Papavinasam, 2013).

Historical Theories of Corrosion

One of essential contributions were made by Faraday (1791- 1867) who established a measurable relationship between chemical activity and electrical current. Ideas on corrosion control began to be produced at the starting of the 19th century (Whitney, 1903). Evans (1923) provided a modern-day understanding of the reasons and also control of corrosion based upon his classic electrochemical theory (Davis 2000; McCarfferty 2010). Now there are many testing standards for corrosion developed by professional societies such as ASTM.

OBJECTIVES

The overall objective was to verify the sensitivity of the new nondestructive two probe alternative current method to detection and quantify the surface and bulk corrosion using steel specimens. The specific objectives were as follows:

- i. Identify the equivalent electrical circuits for the surface and bulk corrosion of steel and represent them in terms of electrical properties of the material using the impedance frequency relationship.
- ii. Investigate the corrosion development (surface and bulk separately) with time for steel specimens placed in 3.5% salt solution and quantify the surface and bulk corrosion along the length of the steel specimens.
- iii. Investigate the corrosion development on the surface of steel pipe placed in moist bentonite clay.
- iv. Compare the standard test results such as weight loss, and visual inspection due to corrosion with the new nondestructive test method where changes in the electrical properties used to quantify the corrosion.

Materials and Methods

Steel Plates and Pipe

Corrosion of carbon steel, ASTM A1018, was used for this study. Based on the manufacturer's data sheet, the iron content varied from 98.8% to 99.3% with a carbon content of 0.18%. For the weight loss and potential difference study the samples used were 3 inches in length. For the electrical characterization of corrosion, the steel bars used were 30 inches in length 1.2 in in width and 0.16 in thickness. Also 2 inch diameter steel pipe was buried in the bentonite clay to evaluate the corrosion. The specific gravity of the carbon steel is 7.86 (ASTM G1-03).

Salt Solution

Both, 3.5% sodium chloride (NaCl) salt solution is representing the sea water and for the accelerated test, 10% sodium chloride (NaCl) solution is representing the hydraulic fracturing fluids with high salt contents, were used. The steel specimens were placed in the selected solution and bentonite clay in a plastic container for the entire duration of testing.

THEORY AND CONCEPTS

VIPULANANDAN IMPEDANCE MODEL (Vipulanandan et al. 2013)

Equivalent Circuit

It is important clearly identify the electrical properties (resistivity (representing resistance R), permittivity (representing capacitance, C) and permeability (representing inductance, L)) of the material that will represent the corroding material. Identification of the most appropriate equivalent circuit to represent the electrical properties of a material is essential to further understand its properties and the changes due to corrosion. In the literature, there are data on impedance frequency responses of materials but there are no clear electrical properties that influence the response.

In this study, different possible equivalent circuits were analyzed to find an appropriate equivalent circuit to represent the corroding steel with two probe monitoring.

CASE 1: General Bulk Material – Resistance and Capacitor

In the equivalent circuit for CASE 1 (Fig. 1), the contacts were connected in series, and both the contacts and the bulk material were represented using a capacitor and a resistor connected in parallel (Fig. 1).

In the equivalent circuit for CASE 1, R_b and C_b are resistance and capacitance of the bulk material, respectively and R_c and C_c are resistance and capacitance of the contacts, respectively. Both contacts are represented with the same resistance (R_c) and capacitance (C_c) as they are identical. Total impedance of the equivalent circuit for Case 1 (Z_1) can be represented as follows:

$$Z_1(\omega) = \frac{R_b(\omega)}{1 + \omega^2 R_b^2 C_b^2} + \frac{2R_c(\omega)}{1 + \omega^2 R_c^2 C_c^2} - j \left\{ \frac{2\omega R_c^2 C_c(\omega)}{1 + \omega^2 R_c^2 C_c^2} + \frac{\omega R_b^2 C_b(\omega)}{1 + \omega^2 R_b^2 C_b^2} \right\}, \quad (1)$$

where ω is the angular frequency of the applied signal. When the frequency of the applied signal was very low, $\omega \rightarrow 0$, $Z_1 = R_b + 2R_c$, and when it is very high, $\omega \rightarrow \infty$, $Z_1 = 0$.

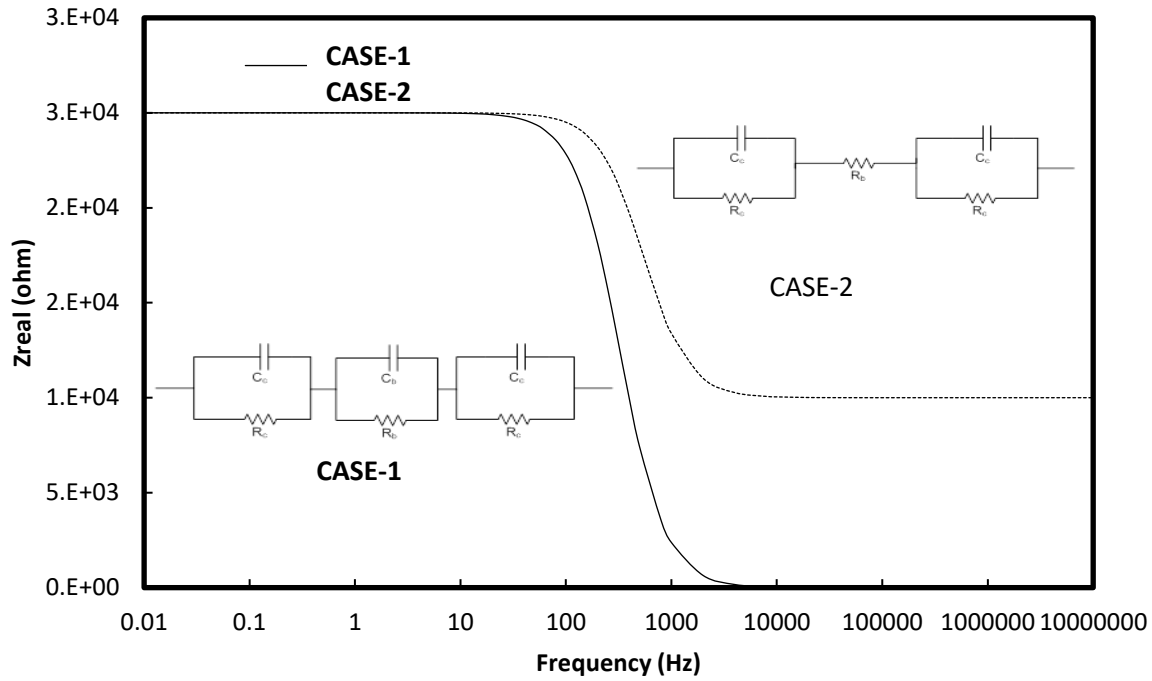


Figure 1 Comparison of typical responses of equivalent circuits for CASE 1 and CASE 2

CASE 2: Special Bulk Material - Resistance Only

In CASE 2 (Fig. 1) as a special case of CASE 1, the capacitance of the bulk material (C_b) was assumed to be negligible.

The total impedance of the equivalent circuit for CASE 2 (Z_2) is as follows:

$$Z_2(\sigma) = R_b(\sigma) + \frac{2R_c(\sigma)}{1 + \omega^2 R_c^2 C_c^2} - j \frac{2\omega R_c^2 C_c(\sigma)}{1 + \omega^2 R_c^2 C_c^2} \tag{2}$$

When the frequency of the applied signal was very low, $\omega \rightarrow 0$, $Z_2 = R_b + 2R_c$, and when it is very high, $\omega \rightarrow \infty$, $Z_2 = R_b$ (Fig. 1).

Steel in Bentonite Clay

The pipe was placed in the moist (40%) bentonite clay and the configuration is shown in Figure 3. The changes in the steel pipe surface were monitored by connecting one probe to the steel pipe and the other to one of the wire probes (C_1, C_2, C_3, C_4).

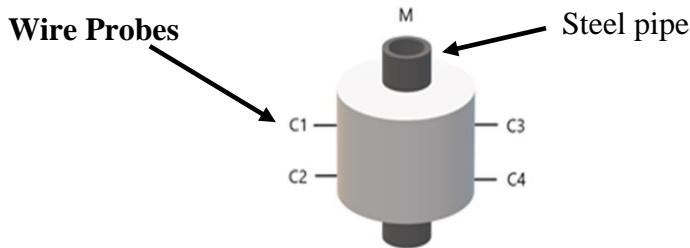


Figure 2 Steel Pipe place in Bentonite Clay Placed in a Plastic Mold

Results, Verification and Discussion

1. Method 1: Weight Loss Study (ASTM G1-03)

Steel samples with a initial length of 3.00 in. and a width of 1.20 in. and thickness of 0.16 in. were used for this experiment. Three specimens were tested. Specimens were placed in 10% sodium chloride solution and tested regularly by cleaning the specimens and measuring the weight and dimensions. In the initial average weight was 812.1 g and it reduced to 803.6 g in one year. The specimens were cleaned using mechanical tools and with were measure after 2, 3, 6 and 12 months. The percentage weight change was related to the testing time (t) (Fig. 3) using the Vipulanandan correlation model (Eqn. (3)) and the relationship is as follows:

$$\frac{\Delta W \times 100}{W} = \frac{t}{A+Bt} \tag{3}$$

Where W was the initial weight of the specimen and ΔW was the weight change. The weight change after one year was 1.05%. The model predicted the test results very well with a coefficient of verification (R²) of 0.99. The parameter A was 4.98 months and parameter B was 0.53. So the ultimate predicted weight change will be 1.88% when the time of exposure is very large (time is infinity).

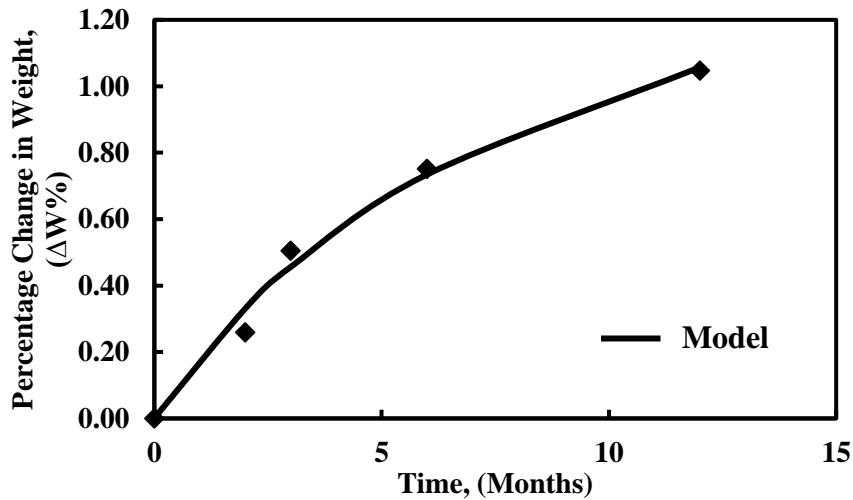


Figure 3. Variation of Weight Loss for the Steel with Time in 10% NaCl Solution

Using the ASTM G1-03 standard the corrosion rate (mm/year) was determined using the following relationship:

$$Corrosion\ Rate = \frac{K \times \Delta W}{Area \times Time\ (hours) \times Density} \tag{4}$$

The carbon steel density was 7.86 g/cm³ and the K parameter for estimating the corrosion rate in mm/year was 8.76x10⁴. The estimate corrosion rate using Eqn. (4) was 1.54 mm/year or 0.06 inches/year in 10% NaCl solution. The estimated rate of corrosion was about three times the corrosion rated reported for sea water (3.5% NaCl) in the literature and hence the results are comparable.

Method 2: Visual Inspection Study

The 30 in long steel specimens placed in 3.5% NaCl solution were visually inspected on a regular basis. Images of the corroded steel surfaces long the length in three locations are shown in Fig. 4 and the corrosion was not uniform and it changed from point to point. As shown in Fig. 5, Locations #2 and #3 showed more corrosion than Location #1. For the new NDT method Locations #1 and #2 were used as the Contacts #1 and #2 respectively.

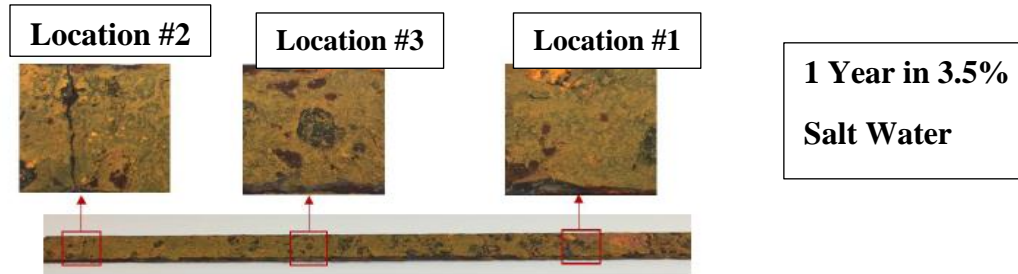


Figure 4. Visual Inspection of Surface Corrosion of Corroded Specimen

Method 3: New Nondestructive Two Probe Resistivity Study (U.S. Patent 2020)

The 30 in long steel specimens placed in 3.5% NaCl solution and steel pipe in clay were tested regularly to detect and quantify corrosion using the two probe alternative current method (Fig. 5). The alternative current frequency was varied from 20 Hz to 300 kHz.

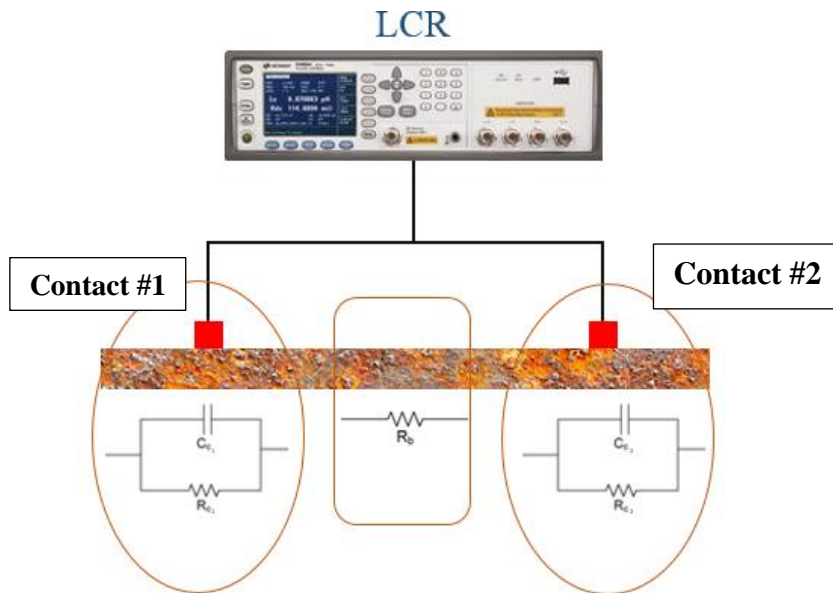
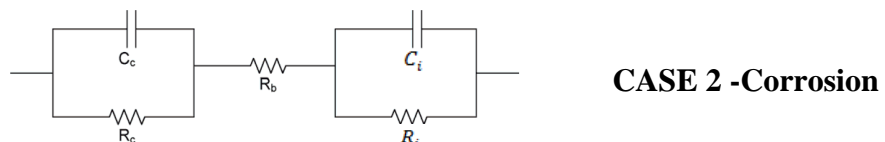


Figure 5. Testing Configuration for the New NDT Resistivity Method

The responses for both non-corroded and corroded steel were CASE 2. This is the identification of the impedance circuit for the current corrosion study (Figure 6 and Eqn. (5)).



$$Z = R_b + \frac{R_c}{1 + \omega^2 R_c^2 C_c^2} + \frac{R_i}{1 + \omega^2 R_i^2 C_i^2} - j \left(\frac{\omega R_c^2 C_c}{1 + \omega^2 R_c^2 C_c^2} + \frac{\omega R_i^2 C_i}{1 + \omega^2 R_i^2 C_i^2} \right) \quad (5)$$

Figure 6. Vipulanandan Corrosion Impedance Model Circuit

Based on the impedance-frequency response of the steel, CASE 2 equivalent circuit was used to determine the contact electrical resistances with time (t) at each contact locations ($R_c(t)$ and $R_i(t)$) and contact capacitances ($C_c(t)$ and $C_i(t)$) on the surface of the steel specimen. During the impedance characterization at least 15 data were collected for each test and the data was used to determine the five unknowns (R_b , R_c , R_i , C_c , C_i) in the Eqn. (5) using the least square method.

The resistance (R) and capacitance (C) for a material between two points of measurements is defined as:

$$R = \rho K = \rho \frac{L}{A} \quad (6)$$

$$C = \epsilon \frac{A}{L} \quad (7)$$

where A = cross-sectional area, L = distance between the two probes, ρ = resistivity of the material, ϵ = absolute permittivity of the material

The product of equations given in (6) and (7) results as

$$RC = \rho \epsilon. \quad (8)$$

Since ρ and ϵ in equations (6) and (7) are material properties, RC at the point of contact is also material property and will be referred as electrical corrosion index. This parameter can be used in characterizing the surface corrosion at each point.

The electrical resistivity (ρ) of the bulk steel specimen was determined from the R_b measured along the length of specimen between the two points of contact and using the Eqn. (6). The initial resistivity of non-corroded steel $\rho_0 = 1.59 \times 10^{-7} \Omega\text{m}$ (Douglas, 1991) and R_0 is the initial resistance measured.

Bulk Corrosion

The impedance-frequency measurements were performed on a weekly basis for 500 days. The frequency range used was from 20 Hz to 300 kHz. The bulk resistance ($R_b(t)$) increased non-linearly with time as shown in Fig. 7. After 500 days of corrosion, the bulk $R_b(t)$ along the length of the corroded steel between Contact #1 (Location #1) and Contact #2 (Location #2) (2 feet apart, Fig 5) increased from 0.131Ω to 5810Ω which showed a change of 44,351 (4,435,100 %).

The resistivity of the corroding steel changed from $1.59 \times 10^{-7} \Omega\text{m}$ to $7.05 \times 10^{-3} \Omega\text{m}$ along the 2 feet length during the testing period of 500 days (Fig. 8), the change is 44,340 times (4,434,000%) which indicated the resistivity was a highly sensing material property to represent the corrosion level within the bulk steel. The change in the electrical resistivity, a material property, is part of the corrosion of the steel, but could not be quantified by any other standard test methods.

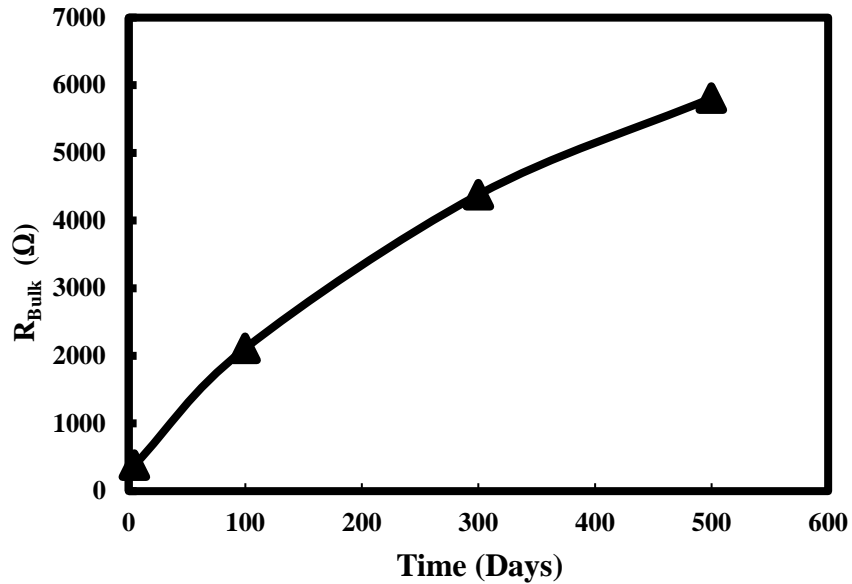


Figure 7. Variation of Bulk Resistance with Time in 3.5% Salt Solution (500 Days)

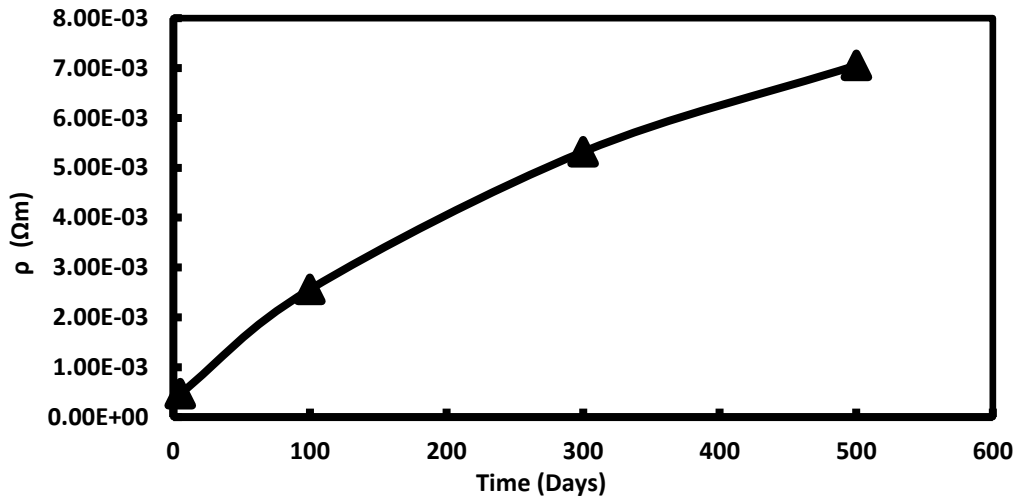


Figure 8. Variation of Electrical Resistivity of the Bulk Steel with Time in 3.5% NaCl Solution

**Surface Corrosion- Contact Corrosion Index (RC)
Steel in 3.5% Salt water**

The variation of contact corrosion index, material property (R^*C), for the corroding steel at Contact #1 in 3.5 % NaCl solution is shown in Figure 9. From the Fig.4, the rust material on the surface of the corroding steel increased with time. The $R_C C_C$ at Contact #1 increased from $5.97 E^{-07} \Omega F$ to $2.24 E^{-06} \Omega F$ during the testing period of 500 days, 2.75 time (275%) increase.

The Contact #2 corrosion index parameter $R_i C_i$ increased from $8.72E-07 \Omega F$ to $2.77E-06 \Omega F$ as shown in Fig. 9. The contact index parameter increased by 2.2 times (220%). The corrosion index parameter after 500 days of testing at Contact #2 was higher than Contact #1, by about 24%.

The corrosion index clearly quantified the surface conditions at the measured two points, and the two points were not the same and also the visual inspection showed the difference on the surface.

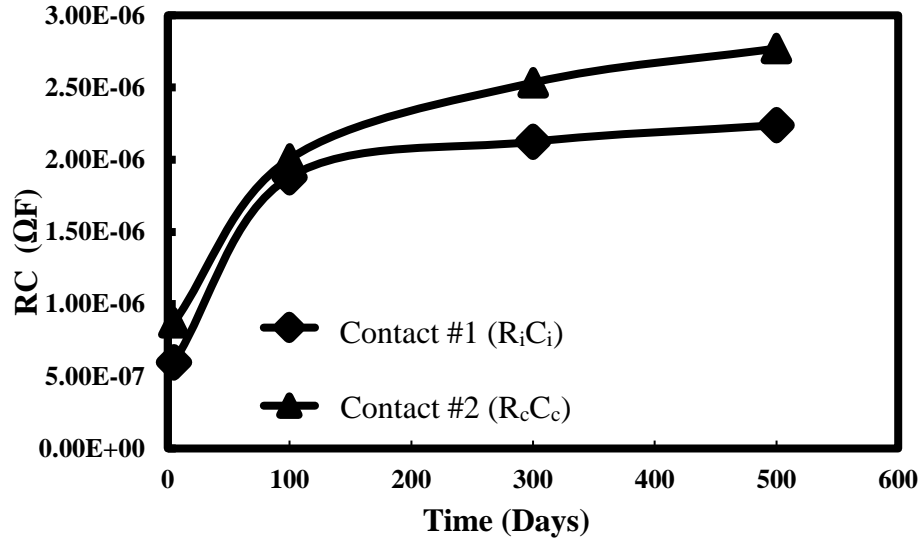


Figure 9. Corrosion Index Parameters for the Two Contact Locations in Fig.4

Steel Pipe in Bentonite Clay

The surface corrosion on the steel pipe was tested for over 600 days. The surface index (RC) changed from $2.4 \times 10^{-3} \Omega F$ to $3.3 \times 10^{-3} \Omega F$, 37.5% increase as shown in Figure 10. This percentage change was less than what was observed in the salt water which varied from 220% to 275%.

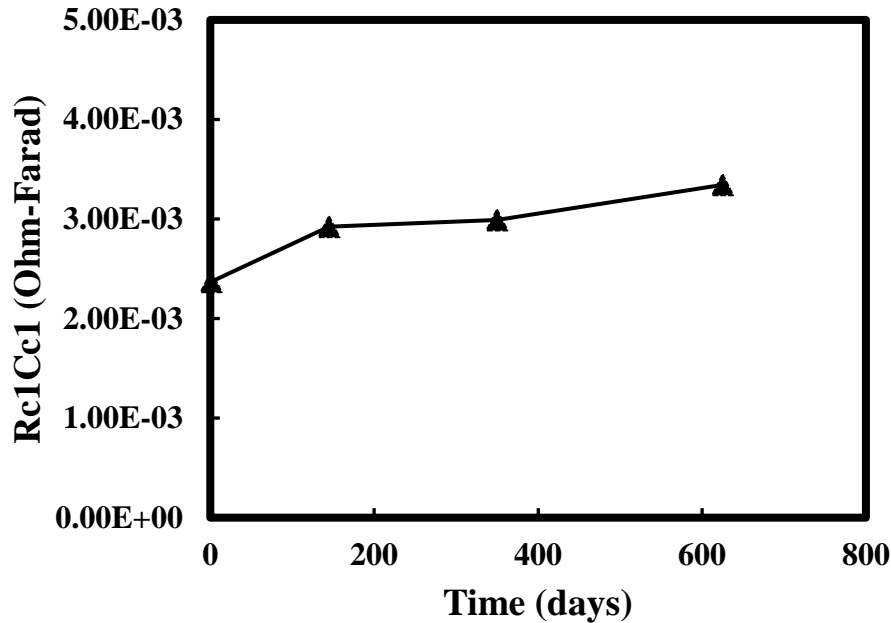


Figure 10. Corrosion Index Parameter for the Steel Pipe Surface in Clay Soil

CONCLUSIONS

In this study the new nondestructive rapid detection and quantification of corrosion was verified and compared with some of the standard test methods using carbon steel. Based on this study following conclusions are advanced:

1. The weight change in steel in 10% NaCl solution in one year was about 1%, and corrosion rate was 1.54 mm/year.
2. The new nondestructive test separated the surface corrosion from bulk corrosion. The method clearly identified resistivity to be a highly sensing material property to characterize the bulk corrosion in steel. The bulk resistivity increase in corroding steel in 3.5% salt solution in 500 days was over 4,430,000%, much more sensitive than the weight loss method and potential difference methods.
3. Also a new corrosion index was developed and verified to characterize and quantify the surface condition on the corroding steel. The corrosion was different at the two tested points and the visual observation verified it. The corrosion index increased in corroding steel in 3.5% salt solution in 500 days was over 200%. The surface corrosion index in the corroding steel pipe in the moist bentonite clay was 37.5% increase in 600 days.
4. Based on the material property changes, the surface corrosion was less than the bulk corrosion in the salt water based on the new test method.

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