

Corrosion Monitoring of Steel Reinforced Concrete Structures Using Embedded Instrumentation

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ABSTRACT

A reinforced concrete corrosivity monitor (RCCM) is an embeddable non-destructive evaluation (NDE) corrosion-monitoring instrument. It is capable of measuring several parameters important to long term corrosion monitoring including linear polarization resistance (LPR), open circuit potential (OCP), resistivity, temperature and a potential related to chloride ion concentration ($[Cl^-]$). Each RCCM unit is a digital peripheral connected on an embedded local area network. The instruments communicate with each other and an external data logger using the SDI-12 industry standard protocol.

The RCCM has many applications in the construction and maintenance of commercial and civil structures. These structures can include high rise buildings, parking garages, bridges, dams, spillways, flood control channels, piers, pylons and erosion control structures. During construction, engineers, builders and supervisors can monitor parameters such as chloride concentration, resistivity and temperature. These parameters can identify errors at an early stage of construction. One error that may be detectable is the use of sea water or contaminated water during mixing of the concrete ($[Cl^-]$). The moisture content and temperature of the structure can be monitored during the curing process to ensure maximum strength of the concrete. Once construction is complete, the instrument can be used to conduct long term monitoring of corrosion conditions over time.

Keywords: rebar, concrete, corrosion monitoring

INTRODUCTION

Corrosion is a wide-spread problem that affects nearly all industry and government sectors. A recent report determined that the direct cost of corrosion in the United States to be 3.1% of the Gross Domestic product (GDP).¹ This corresponds to \$300B annually or \$1000 per person. This figure includes only the *direct* costs (e.g., corrosion prevention, corrosion inspection, and replacement or refurbishment of corroded structures). The *indirect* costs (e.g., lost productivity, taxes, and overhead) were conservatively estimated to be equal to the direct costs.

The nation's infrastructure is aging and maintenance budgets are inadequate to prevent corrosion. New construction and major repairs/refurbishment are being reduced or delayed so that current hardware and structures must last longer than their design lifetimes. For example, bridges are being restricted or closed on a daily basis as safety engineers raise concerns about corroded decks and structural members. Out of ~570,000 bridges in the National Bridge Inventory, over 100,000 are considered structurally deficient.² It is estimated that \$78B will be spent over the next 20 years in major rehabilitation of bridges.³ However, this expenditure only maintains the *status quo*, i.e., as many bridges become newly deficient as are refurbished.⁴ More than a third of the highways are in poor or mediocre condition. Increased traffic and larger trucks place greater loads on highways and bridges. It is estimated that inadequate roads cost the economy \$50B per year in 2005.⁵

Corrosion is also a safety issue. Undetected or unheeded corrosion of bridges and other structures can cause catastrophic failure with loss of life. Two corrosion-induced bridge collapses are the Silver Bridge over the Ohio River in 1967 and the I-95 Mianus River Bridge in Connecticut in 1983.⁶ The Silver Bridge failed from corrosion cracks in an eyebar while corrosion of a pin-and-hanger assembly caused the Mianus River Bridge collapse. Other bridges have required emergency or accelerated repairs, closure, or traffic restrictions because of corrosion, including:⁶

- Harvard Bridge in Cambridge, MA
- Yankee Doodle Bridge (I-95) in Norwalk, CT
- Southeastern Pennsylvania Transportation Authority (SEPTA) Bridge in Philadelphia
- Williamsburg Bridge in New York City
- Ben Franklin Bridge in Philadelphia
- Royal Gorge Bridge in Colorado
- Portsmouth Bridge over the Ohio River
- Tower Bridge in London
- Lake Maracaibo Bridge in Venezuela.

In extreme cases, the corrosion can be rapid enough to require repair or component replacement after only 2-4 years of service.⁶ The rate and extent of corrosion depends on many factors including construction materials, paint or other corrosion protection system used, presence of marine or road salt, amount of precipitation, air pollution, temperature and stray currents.⁷ Unfortunately, the environments to which many bridges are exposed are the same environments that promote corrosion.

Civil structures such as bridges and dams are extremely large construction efforts costing millions to billions of dollars and spanning several years. In the United States alone repairs for corrosion damage to federal bridges are estimated at \$50 billion annually. These structures are vital to commerce and the standard of living of millions of people in the United States and billions of people worldwide. Worldwide estimates to repair reinforced concrete structures are \$200/m² of exposed surface. Premature or unexpected failures of these structures are often catastrophic in terms of time, money and lives. The high costs of corrosion due to replacement and premature failures mandate the need for integrated in-situ NDE systems. These NDE systems should provide information based on changes in the structure's corrosion condition to affect timely maintenance interventions.

Until now corrosion monitoring in steel reinforced structures has been conducted using embeddable probes. The probes measure analog signals that can be interrogated using electronic devices external to the structure. Since the signals produced by these probes are small in amplitude, they are subject to

corruption from nearby EMI sources such as power lines, radios, cell phones and therefore must have limited lead lengths. To address these limitations, a reinforced concrete corrosivity monitor (RCCM) has been developed that incorporates all required electrodes and signal processing electronics. The approach allows the leads connecting the low-level analog signals to signal processing electronics to be kept short (approximately 1 inch or 2.5 cm). Short analog signal leads allow for a higher signal to noise ratio and more accurate and repeatable measurements. The RCCM communicates with other instruments and an external datalogger using a digital protocol which is highly resistant to corruption from nearby EMI sources.

EXPERIMENTAL PROCEDURE

The RCCM is mounted to the rebar system during construction or major repair/refurbishment (**FIGURE 1**). It monitors four key factors in corrosion - linear polarization resistance (R_p), open circuit potential, resistivity, and chloride ion concentration, plus temperature. Each of these parameters measured by the RCCM is linked to the corrosivity of the concrete. If concrete were a simple physical and chemical system, measuring only one parameter would be sufficient. However, concrete is a dynamic, highly variable system that interacts with the external atmosphere in myriad ways. As such, measurements of any *single* parameter can become uncorrelated with corrosivity, leading to incorrect interpretations. By using multiple inputs, the robustness of the decision system is increased, as one anomalous parameter will not affect the corrosivity analysis.



FIGURE 1. RCCM Installed on a Rebar Grid.

In several publications,^{8- 13} the parameters used by the RCCM have been deemed important in gaining insight to better understand the corrosion conditions present on the reinforcing steel. The R_p value can be directly related to the instantaneous corrosion rate of the steel sensor, *when correctly normalized for the active area and if the relevant electrochemical parameters are known*. The concrete resistivity influences the ability of anodic and cathodic regions on the steel to interact, with higher resistivities hampering that interaction, and *generally* leading to lower corrosion rates. The electrochemical reactions involved in corrosion as well as the movements of ions through solution are thermally activated processes, and increased temperature *generally* leads to increased corrosion rates. The OCP value has been correlated to the likelihood of active corrosion on steel in concrete, *albeit with some caveats*. The italics are the reason for a multi-probe approach. By combining the results of the four parameters that are individually important, but are measured independently, the confidence in the final assessment is enhanced.

Linear Polarization Resistance (LPR or R_p) and Open Circuit Potential (OCP or E_{corr}): The RCCM measures linear polarization resistance by using a steel working electrode, stainless steel counter electrode, and manganese dioxide reference electrode. The working electrode is a sacrificial component made of black steel, designed to corrode at the same rate as the rebar steel. Defective areas in protective coatings over structural steel, such as epoxy or stainless steel cladding, may be expected to demonstrate corrosion characteristics comparable with those of black steel.

The RCCM control module initiates the measurement of open circuit potential between the working and reference electrodes in the potentiostat circuit, and applies the appropriate potentiostat drive potential between the counter and working electrodes. A zero resistance ammeter (ZRA) in the potentiostat circuit measures the cell current.

The RCCM scans cell current and potential over a range about the OCP, and uses the resulting data to calculate polarization resistance. The corrosion rate of reinforcement steel may be expected to be inversely proportional to this value. If LPR is high and OCP remains small in magnitude (greater than $-200\text{mV}(\text{Cu}/\text{CuSO}_4)$,¹⁴ managers may anticipate that the reinforcement steel in a structure is passive, undergoing corrosion at a relatively low rate. As steel begins to depassivate, due to an increase in chloride ion concentration or other corrosive environmental conditions, LPR will decrease and OCP will become increasingly negative.

Resistivity: The RCCM uses four stainless steel electrodes to measure resistivity in the concrete that surrounds it. A galvanostat circuit drives a stepped current through the outer pair of these electrodes, and measures the potential between the inner pair at each step. Electronics within the RCCM then perform a linear regression to calculate the resistance between the inner pair of electrodes. The RCCM multiplies this value by the cell constant of its resistivity sensor to derive the resistivity of the concrete in units of ohms-cm. This provides information on the relative amount of moisture in the concrete. Structure managers may also use this resistivity parameter with the geometric cell constant of the working, counter, and reference electrodes to correct for ohmic resistance errors in polarization resistance measurements.

Chloride Ion Concentration: The RCCM uses a silver/silver-chloride ion specific electrode in combination with its reference electrode to measure chloride ion concentration. Over time, a potential will develop between the Ag / AgCl and reference electrodes. The magnitude of this potential is related to the chloride concentration in the concrete surrounding the instrument. The RCCM reports chloride measurement results as a potential. As the electrodes age, potential drift becomes important and dominates the measurement. After five to seven years, this measurement is not considered reliable.

Temperature: The RCCM includes an on-board solid state sensor, which provides information on the temperature within the concrete surrounding it.

The RCCM integrates processing electronics with its sensors, and so can use digital, rather than analog communications. This eliminates data corruption by electro-magnetic interference from power lines, radio waves, and cellular telephones. Digital technology also makes it possible to connect multiple RCCM monitors to a single datalogger, saving potentially tens of thousands of dollars in support electronics per project.

RESULTS

The Seohae Grand Bridge in South Korea (**FIGURE 2**) illustrates the use of the RCCM. It is the longest bridge in South Korea, which is connected Pyeongtaek-Si in Gyeonggi-Do to Dangjun-si in Chungbuk-Do, crossing the Asan Bay in the West Sea of



FIGURE 2. Seohae Grand Bridge

Korea. Its total length is 7,310m. It was completed in 2000.

RCCMs were installed in two piers at three locations: above the sea (Ch 1), splash zone (Ch 2), and tidal zone (Ch 3) as shown in **FIGURE 3**. The installation was a retrofit with a small volume of concrete being removed from the pier, the RCCM mounted on the rebar, and the pier patched (**FIGURE 4**). The RCCM measurements are sent to a data logger and then sent via a cell phone modem to the Maintenance Office.

Initial results are given in **FIGURE 5**. It is important to note that the measurements are of fresh concrete repair patches and may differ from fully cured concrete. We will first discuss what to expect from fully cured material and then discuss what may be different from new material.

ASTM* C-876 indicates the OCP or E_{corr} varies with the probability of corrosion (**TABLE 1**). These ranges are based on wide experience of corrosion in chloride contaminated concrete bridge decks, but when carbonation is the cause of corrosion or cathodic processes are modified, the range of the corrosion potential may be different. Arup¹⁵ reports a similar distribution of OCP/ E_{corr} values for different types of corrosion (**TABLE 2**).

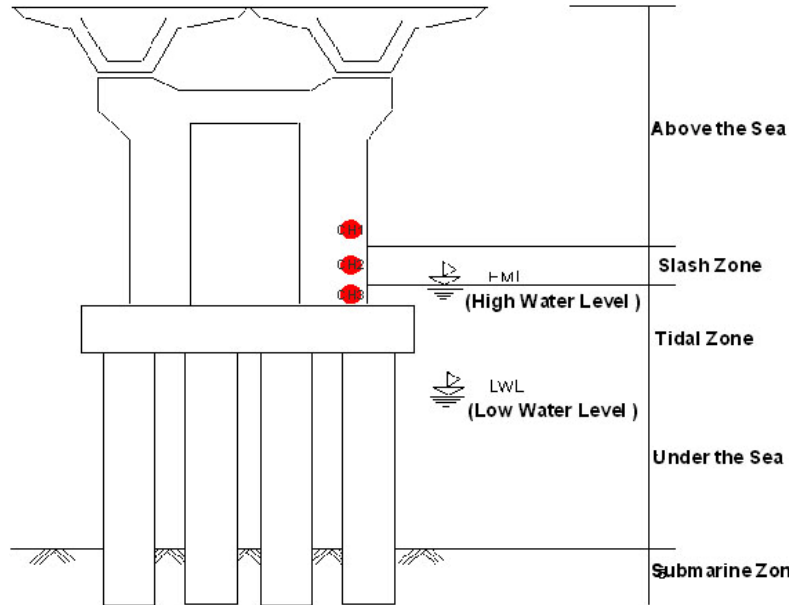


FIGURE 3. Pier Schematic Showing Location of RCCMs.



FIGURE 4. Installation of an RCCM on a Bridge Pier.

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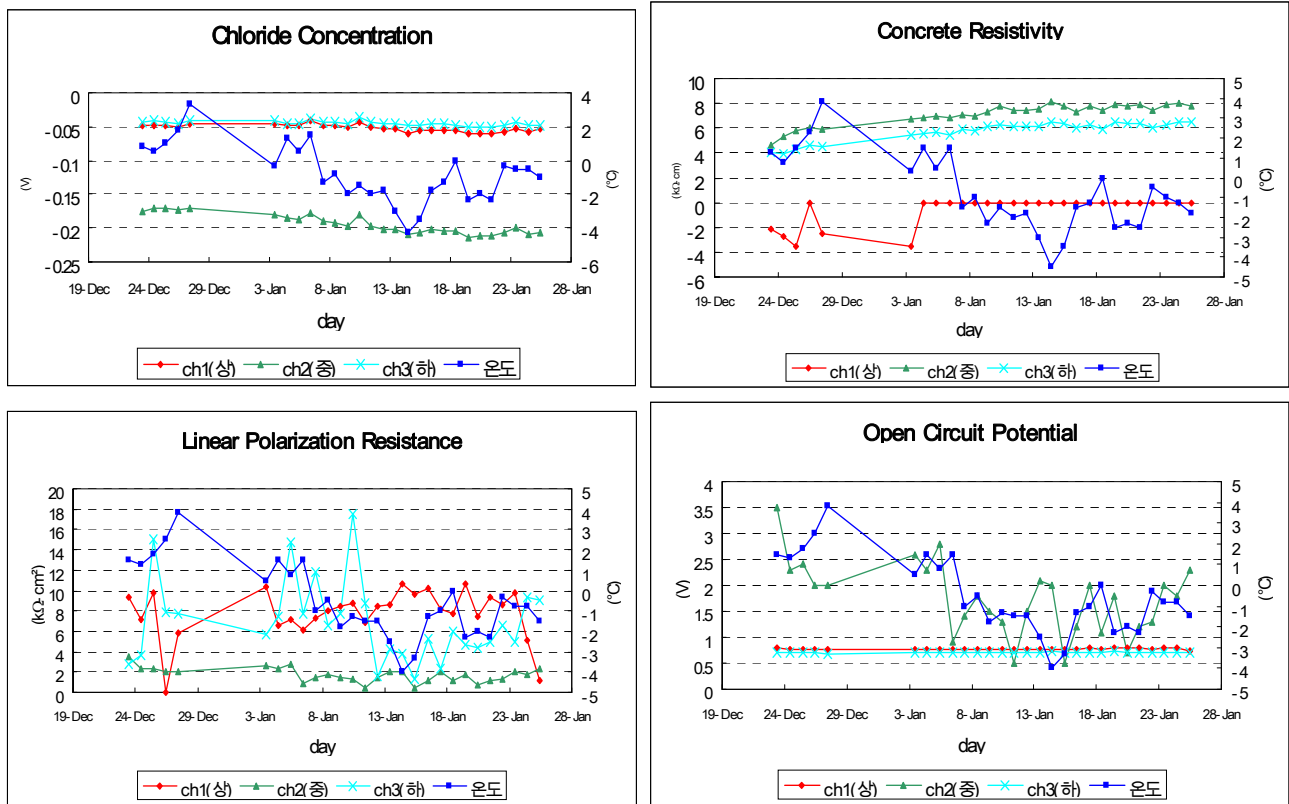


FIGURE 5. Initial Results from RCCMs Installed on the Seohae Grand Bridge. As Corrosivity Increases, the Graphed Parameters Exhibit the Following Trends: V_{Cl} Decreases; Concrete Resistivity Decreases; LPR Decreases; OCP Decreases.

TABLE 1. PROBABILITY OF CORROSION FOR DIFFERENT E_{CORR} VALUES¹⁴

Probability of corrosion	E_{corr} (vs Cu/CuSO ₄)	E_{corr} (vs SCE)	E_{corr} MnO ₂
> 95 %	< -350 mV	< -276 mV	< -430 mV
< 5 %	> -200 mV	> -126 mV	> -280 mV
approx. 50%	-200 to -350 mV	-126 to -276 mV	-280 to -430 mV

TABLE 2. TYPICAL E_{CORR} VALUES OF THE DIFFERENT CORROSION STATES OF STEEL IN CONCRETE

Corrosion state	Range of possible E_{corr} /mV _(SCE)	Converted to mV _(MnO2)
Passive state	+200 to -200	40 to -360
Pitting corrosion	-200 to -500	-360 to -510
General corrosion	-450 to -600	-610 to -760
Corrosion with limited oxygen access	Around -1000	-1160

There is extensive evidence the R_p is inversely proportional to the dissolution rate for a material undergoing uniform dissolution. For steel in concrete, the transition from the passive state to an actively corroding state is accompanied by a substantial change in the polarization resistance as shown in **TABLE 3**.⁸ Thus, an accurate measurement of the R_p of a structure would allow a direct calculation of the thinning rate of the steel, if the active area were known.

As long as the polarization resistance remains high and the open circuit potential is noble (usually $> -0.2 V_{scc}$), the reinforcement steel is passive and corroding at a very small rate. As the steel begins to depassivate due to an increase in $[Cl^-]$ or other corrosive environmental conditions, the OCP will become more negative accompanied by a decrease in the polarization resistance.

TABLE 3. TYPICAL R_p VALUES

Specific polarization resistance (R_p) $k\Omega\text{ cm}^2$	
Passive steel state (Laboratory)	> 500
Passive steel field (current not well contained)	~ 50 or larger
Corroding	< 10 (if < 2 heavily corroding)

The temperature of the structure influences the corrosion process of steel in concrete, especially on the corrosion potential and on the corrosion rate (R_p values). Transport processes as well as the electrolytic concrete resistivity strongly depend on the physicochemical properties of the pore water solution. The most important parameter is supposed to be the viscosity of water. The temperature dependence of the viscosity of water is mainly important for how it affects the concrete resistivity and diffusion processes.^{16,17}

Concrete resistivity is a geometry-independent material property that describes the resistance to the flow of charge. The resistivity of concrete may vary over a wide range, from 10^1 to $10^6 \Omega\text{ m}$, influenced by the moisture content of the concrete (environment) and the concrete composition. In concrete, the current is carried by ions dissolved in the pore liquid. More pore water (wet concrete) as well as more and wider pores [high water to cement ratio (w/c)] cause a lower resistivity. For a constant moisture content, the resistivity is increased by a lower w/c, longer curing hydration and by the addition of reactive minerals such as blast furnace slag, fly ash and silica fume. The resistivity increases when the concrete dries out and when it carbonates in Portland cement concrete. The effect of the penetration of chloride ions is relatively small. However, within a particular structure, more permeable spots will have a comparatively low resistivity and stronger chloride penetration.

Resistivity is usually a good indication of the transport rate of the corrosion front through the concrete. Several researchers have suggested that one can relate the concrete resistivity and likeliness of corrosion. Three sets of data are shown below: McCarter¹⁸ (**TABLE 4**), Langford¹⁹ (**TABLE 5**), and Bertolini⁹ and Boomfield²⁰ (**TABLE 6**).

TABLE 4. EMPIRICAL CONDUCTIVITY THRESHOLDS FOR DEPASSIVATED STEEL REINFORCEMENT

Resistivity $k\Omega\text{-cm}$ (Conductivity, S/m)	Probable Corrosion Rate
$(< 5\text{ k}\Omega\text{-cm}) (> 2 \times 10^{-2})$	Very High
$(5\text{ to }10\text{ k}\Omega\text{-cm}) (1\text{ to }2 \times 10^{-2})$	High
$(10\text{ to }20\text{ k}\Omega\text{-cm}) (1 \times 10^{-2}\text{ to }5 \times 10^{-3})$	Moderate/low
$(> 20\text{ k}\Omega\text{-cm}) (< 5 \times 10^{-3})$	Low

TABLE 5. MEASUREMENTS ON DEPASSIVATED STEEL USING WENNER FOUR POINT PROBE

Resistivity	Probable corrosion rate
>20 kΩ cm	Low corrosion rate
10- 20 kΩ cm	Low to moderate corrosion rate
5 to 10 kΩ cm	High corrosion rate
< 5 kΩ cm	Very high corrosion rate

TABLE 6. CORRELATION BETWEEN CORROSION RATE AND RESISTIVITY USING A FIELD LINEAR POLARIZATION DEVICE

Resistivity	Probable corrosion rate
> 100-200 kΩ cm	Cannot distinguish between active and passive steel – negligible corrosion, concrete too dry
50 – 100 kΩ cm	Low corrosion rate
10 – 50 kΩ cm	Moderate to high corrosion where the steel is active
< 10 kΩ cm	Resistivity is not the controlling parameter

The relationship shown in the above tables were derived after analyzing measurements of corrosion rate and resistivity, with Tables 4 and 5 showing the same ranges. **TABLE 6** shows resistivity values that are larger for corresponding conditions shown in **TABLE 4** and **TABLE 5**, which could be explained by different concrete mixtures of more recent concrete structures.

The pore system in hardened cement paste is a major factor influencing corrosion. The electrical resistivity of the concrete is greatly influenced by its moisture content, by the ionic composition of the pore water, and the continuity of the pore system in the hardened cement paste. Thus a concrete with high electrical resistivity will be less susceptible to corrosion. Saturated concrete has a resistivity between 1 to 20 kΩ-cm, depending on mix parameters, while dry concrete. However, under certain circumstances, it is still possible to have a concrete with high concrete resistivity (but with high moisture content) and low R_p , but where this low R_p value is a reduction from earlier high R_p .

A generally applicable table for assessment is shown in Table 7.

TABLE 7. GENERALLY APPLICABLE ASSESSMENT OF PARAMETERS

R_p	OCP	Resistivity	Likelihood of Corrosion
Low	Low		Highly Likely
High	Low	Low	Unlikely if concrete is immersed
Low/Medium	Low	High	Likely, but a a modest rate
High	High	High	Unlikely

If low R_p and resistivity values are accompanied by E_{corr}/OCP values < -700 mV_{sce}, then the oxygen limitation is likely taking place and the corrosion rate is limited. However, as the passive film thickens (assuming that no chlorides are present) in the high pH of the concrete pore solution, the measured value of R_p will increase. This has been seen in other installations. In summary, early in the life of the structure the R_p values measured are expected to fluctuate, as it seen in **FIGURE 5**.

The discussion above has mainly focused on fully cured, intact concrete as it is the material of greatest interest. However, the data presented in FIGURE 5 are from a fresh concrete patch. Longer term measurements would be very illustrative; however, they have not yet been supplied to us. It is also useful to note possible differences between fresh and cured materials. The measured R_p and resistivity at early times might be low, due to high moisture content. The low resistivity might be due to the concrete being fresh cured and the pores filled with high moisture content. The low R_p could be due in part to a high saturation state of the pore solution and/or that the passive layer on the working electrode is just being formed or not having reached a pseudo steady state with the pore solution.

Alternatively, it appears that the splash zone (Ch 2) unit is indicating high corrosivity. Given that rebar corrosion should not have commenced in such a short time, it is possible that the concrete patch is defective. For example, if the patch had cracks, it would readily allow sea water ingress and rebar corrosion to commence. For the other two locations, above the sea (Ch 1) and tidal zone (Ch 3), only the concrete resistivity for Ch 1 indicates corrosion; this reading may be anomalous.

CONCLUSIONS

Five sets of measurements have been successfully obtained from three RCCM placed in a pier on the Seohae Grand Bridge in South Korea. Initial results show the instruments and the communication equipment are working properly.

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