2019 Award Nomination

Title of Innovation:

The Connectionless Electrical Pulse Response Analysis (CEPRA) method

Nominee(s)

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Category:

Testing

Dates of Innovation Development:

from January 2012 to July 2015

Web site:

www.giatecscientific.com

Summary Description:

The corrosion rate of rebar in concrete traditionally has been determined using polarization methods such as the potentiostatic, galvanostatic or potentiodynamic techniques. These techniques are rather slow, and all require having an electrical connection to the rebar, which in turn requires damaging the concrete cover. Therefore, despite the satisfactory accuracy, these techniques have been rarely used for civil engineering structures. The recently developed Connectionless Electrical Pulse Response Analysis (CEPRA) method eliminates the need to have a rebar connection and allows the determination of corrosion rate in less than 10 seconds per measurement. This enables the user to perform corrosion investigations with minimal disruption to the concrete element and also decreases the time required to inspect large structures. The method is based on using a Wenner array probe (a four-point probe) along the rebar under consideration and monitoring the potential difference between the two inner probes following the application of a step voltage from the outer probes. Using the potential difference between the two inner probes, the characteristics of the system, including the concrete resistivity and the polarization resistance/corrosion rate can be determined using a circuit model that is outlined in this document. The technique has been commercialized as a hand-held device (iCOR®) and has been used in several laboratory and field studies in which its accuracy has been found to be similar to other well-established methods.

Full Description:

(Please provide complete answers to the questions below. Graphs, charts, and photos can be inserted to support the answers.)

1. What is the innovation?

The Connectionless Electrical Pulse Response Analysis (CEPRA) technique is a method to determine the corrosion rate of reinforcing steel embedded in concrete in a connectionless manner, through the use of a four-probe array (Wenner probe) on the concrete surface. While traditional corrosion rate monitoring methods, such as galvanostatic/potentiostatic methods require establishing a connection to the reinforcing steel network to determine the open-circuit potential and its perturbation, in the CEPRA method, the reinforcing steel impedance response, and the corrosion rate, are determined without requiring a direct connection.

2. How does the innovation work?

The CEPRA method uses a four-probe array with the probes being in line with the reinforcement under consideration, as shown in Fig. 1. The two outer probes are used to apply a step voltage, after which the potential difference between the two inner probes is determined for a period of 6 to 10 seconds. From this, the concrete resistivity and the rebar polarization resistance can be determined.

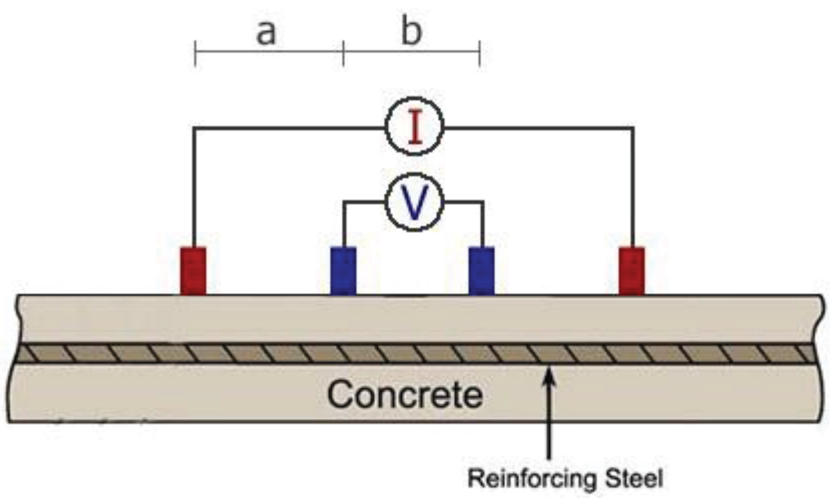

Figure 1 The configuration of the Wenner probe on the surface of concrete

When a current pulse or a step voltage is applied from the two outer probes of a Wenner probe, this current has two primary flow paths. One path is normal to the metallic electrode, which causes the charging of the double-layer capacitance or the polarization of the electrode (depending on the frequency of the applied current); another path is parallel to the metallic electrode, in which the current applied by one of the outer probes is consumed by the other. The portion of current flowing in each of these paths is dependent on the applied current's frequency, the concrete cover characteristics (cover depth and concrete resistivity), the polarization resistance value, the rebar diameter, and the double-layer capacitance. These are all interrelated factors that affect the current flow path and the obtained results. This system can be represented schematically using the circuit model shown in Fig. 2.

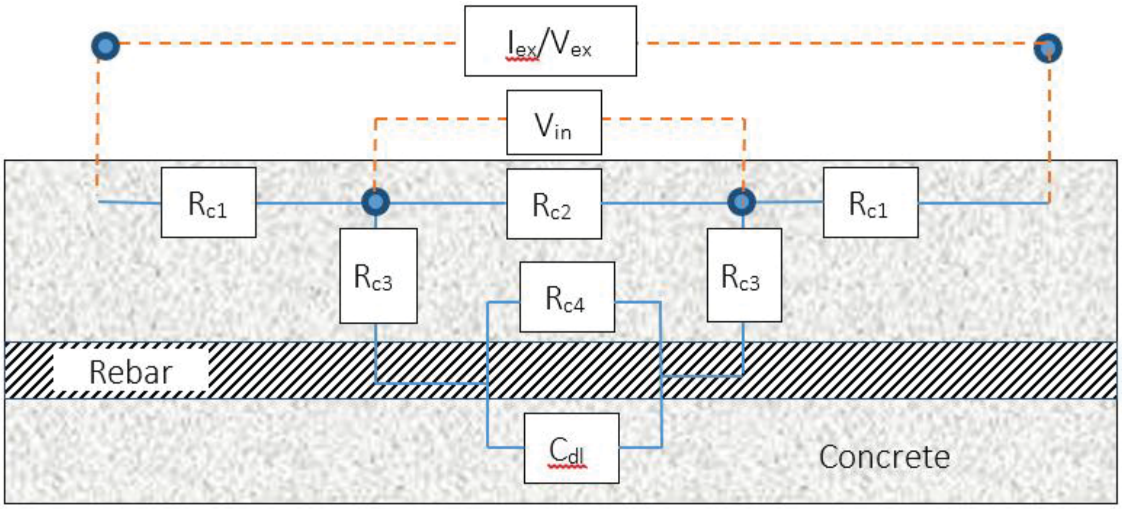

Figure 2 Circuit model used to represent the CEPRA method

In this case, Rc_1 represents the probes' contact resistance, and all of the current is faced by this resistance, while Rc_2 represents the current flow path between the two probes (the path not polarizing the rebar) and Rc_3 represents the current flow path that polarizes the rebar or charges the double-layer capacitance. The magnitude of current passing by each of these resistors is dependent on: (1) the magnitude of their resistance, (2) the impedance caused by the capacitance or the extent of charging of this capacitance, (3) the magnitude of the polarization resistance, (4) the concrete cover depth and reinforcement diameter, and (5) the frequency of the applied current. This circuit can be solved in order to determine the polarization resistance (Rc_4 in Fig. 2), if the current applied from the two outer probes is swept from very high to very low frequencies. However, this is a very time-consuming measurement that may take several minutes to a few hours depending on the circuit's time constant. Alternatively, the components of this system can be retrieved if the response (i.e., voltage difference between the two inner probes) to a narrow DC/AC current or voltage pulse applied from the outer probes for a short period of time is fitted to the theoretical transient obtained from this circuit. In these cases, the measured voltage response as a factor of time is similar to that of a charging RC circuit, as shown in Eq. 1, assuming that the electrolyte/concrete capacitance is negligible.

$$V_{in}(t) = V_{ex}(A - Be^{-Dt}) \quad \text{(Eq. 1)}$$

where V_{ex} is the constant voltage applied through the external electrodes and V_{in} is the potential difference measured between the two inner electrodes.

The model shown in Fig. 2 is solved in order to determine the variables A, B, and D. It was found that these variables follow functions shown in Eqs. 2, 3, and 4. By measuring the voltage response over time, A, B, and D can be calculated by fitting Eq. 1 to the measured data. Such a circuit can be solved if the cover depth is known. This is because the cover depth provides an indirect measure of the ratio of current flowing through Rc_2 to that flowing through Rc_3.

$$A = f\left(R_{c1}, R_{c2}, R_{c3}, R_{c4}\right) \quad \text{(Eq. 2)}$$

$$B = g\left(R_{c1}, R_{c2}, R_{c3}, R_{c4}\right) \quad \text{(Eq. 3)}$$

$$D = h\left(R_{c1}, R_{c2}, R_{c3}, R_{c4}, C_{dl}\right) \quad \text{(Eq. 4)}$$

After Rc_4 (which is the polarization resistance, R_p) is determined, the corrosion rate can be found using the Stern and Geary equation. The concrete resistivity can also be determined using Rc_2 and Rc_3. More information on the background of the technique and a more in-depth discussion of the underlying circuit model can be found in: A. Fahim, P. Ghods, R. Alizadeh, M. Salehi, S. Decarufel (2018) "CEPRA - A new test method for rebar corrosion rate measurement" *ASTM STP 1609*.

3. Describe the corrosion problem or technological gap that sparked the development of the innovation? How does the innovation improve upon existing methods/technologies to address this corrosion problem or provide a new solution to bridge the technology gap?

The corrosion rate of rebar in concrete traditionally has been determined using polarization methods such as the potentiodynamic technique, galvanostatic pulse technique, potentiostatic pulse technique, and, in some cases, the electrochemical impedance spectroscopy for laboratory application. Although these techniques have been very successful in the laboratory, the techniques have not been widely used for field applications in the civil engineering community. This can be attributed to the following reasons: (1) The concrete cover has to be damaged in order to establish a connection to the rebar network, which calls for subsequent patching/repair measures; (2) the polarized area has been a large source of uncertainty, especially in cases of macrocell corrosion and passive reinforcements; (3) a number of these techniques, such as electrochemical impedance spectroscopy (EIS), are very time-consuming and therefore cannot be used to map corrosion rates for large areas; and (4) existing techniques that do not require a long measurement time (< 10 seconds per measurement) do not provide reliable results for passive reinforcements, due to the large amount of time required for passive electrodes to reach quasi-steady-state conditions.

The barrier to implementing corrosion monitoring methods in the field is therefore evident from the aforementioned discussion. The availability of a connectionless method to determine the corrosion rate provides engineers/inspectors with a practical tool to investigate the possibility of corrosion initiation, for large reinforced concrete members, in a timely manner with minimal disruption to the concrete cover. This, in turn, enables engineers/inspectors to: (1) predict of the residual structural service-life of reinforced concrete members; (2) prioritize areas in need of repair; (3) predict the time to the next repair event; (4) assess the structural reliability of reinforced concrete members (5) differentiate areas degrading due to corrosion from areas suffering other degradation mechanisms.

4. Has the innovation been tested in the laboratory or in the field? If so, please describe any tests or field demonstrations and the results that support the capability and feasibility of the innovation.

The the device implementing the CEPRA method has been used in several experimental studies both in the laboratory and in the field and the algorithm behind the CEPRA method has also been studied numerically using finite element simulations. One of the laboratory studies was done in collaboration with the University of New Brunswick, in which the researchers have prepared reinforced concrete samples with various contents of admixed chlorides (0%, 1.5%, 3% and 6% by weight of cement) and embedded reinforcements with different diameters (10 and 20 mm) at different depths from the surface (20, 40 and 70 mm). The samples were exposed to an environment of high humidity to accelerate corrosion propagation and the corrosion rate was monitored for 8 months using the CEPRA method. At the end of the exposure period, the embedded reinforcements were extruded from the concrete and their mass loss was determined using ASTM G01 method, from which the average corrosion rate was calculated through Faraday's law; for the purpose of comparing the actual corrosion rate to that predicted through the CEPRA method. Fig. 3 shows the comparison between the actual corrosion rate, determined gravimetrically, compared to that found through the method. The results clearly show the reliability of the method in determining corrosion rates accurately. For actively corroding reinforcements, the ratio between the actual and predicted corrosion rates generally fell in the accuracy range accepted by the literature, shown by the dashed lines (0.5 to 2 times the actual corrosion rate). This range is typically cited in the literature due to the uncertainty of the beta coefficient, used in the Stern and Geary equation, which has been shown to range between 13 and 52 mV for similar conditions of carbon steel embedded in concrete. This accuracy is very similar to that obtained through the well-established galvanostatic method, which is shown in Fig. 4. For passive reinforcements (reinforcements exposed to concrete not contaminated with chlorides), the predicted corrosion rates fell in the range of 0.05 to 0.25 μA/cm^2 in the dry/semi-saturated concrete condition or when 20-mm reinforcements were used. This is generally the same range of corrosion rates shown by passive reinforcements for other well-established methods. When testing passive reinforcements with small diameters in the saturated concrete condition, the passive corrosion rate was overestimated to the range of 0.6 to 0.8 μA/cm^2. Despite this overestimation, passive samples could be differentiated from actively corroding samples. It is also worth mentioning that the overestimated passive corrosion rates were still lower than that determined using the galvanostatic method as shown in Fig. 4. These results clearly show the accuracy of the method and how it compares to one of the most widely used corrosion inspection method in the civil engineering domain (the galvanostatic method). It is worth mentioning that this accuracy was not only obtained in a connectionless manner but also using a measurement time of only 6 seconds, which is significantly lower than that typically used for other methods. A more detailed discussion on the accuracy and limitations of the method and a more elaborate experimental comparison between this method and the potentiodynamic, coulostatic and AC impedance methods can be found in: Fahim, A., Ghods, P., Isgor, O., & Thomas, M. (2018; in press). A critical examination of corrosion rate measurement techniques applied to reinforcing steel in concrete. Materials and Corrosion, doi:10.1002/maco.201810263

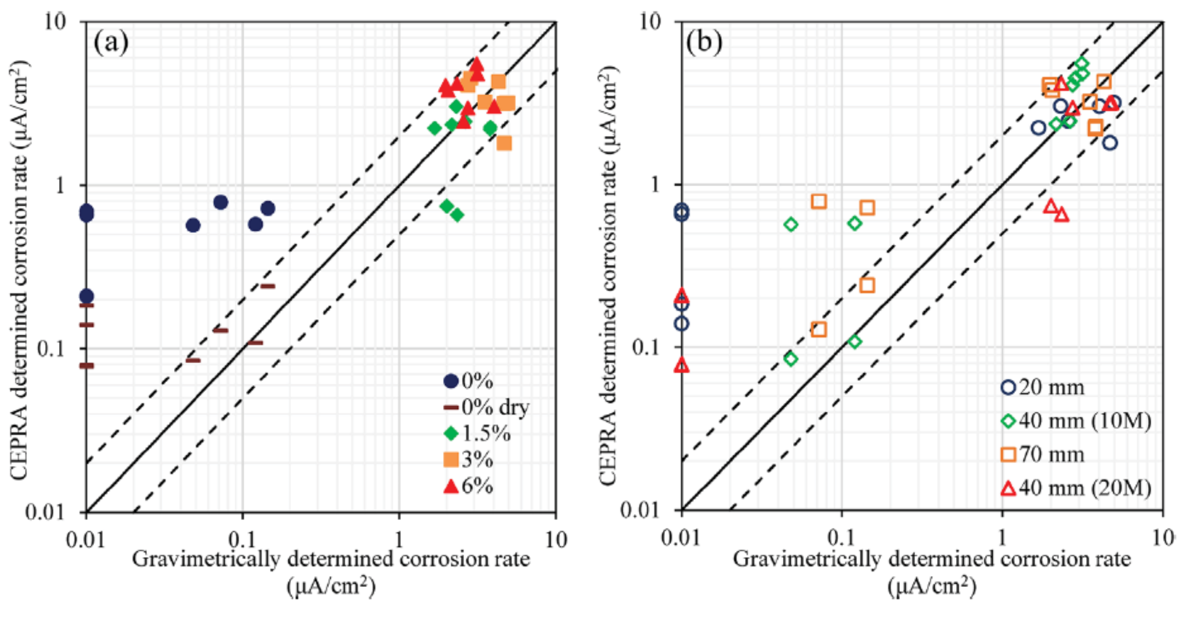

Figure 3 Comparison between the corrosion rate determined through the CEPRA method and that determined gravimetrically through ASTM G01

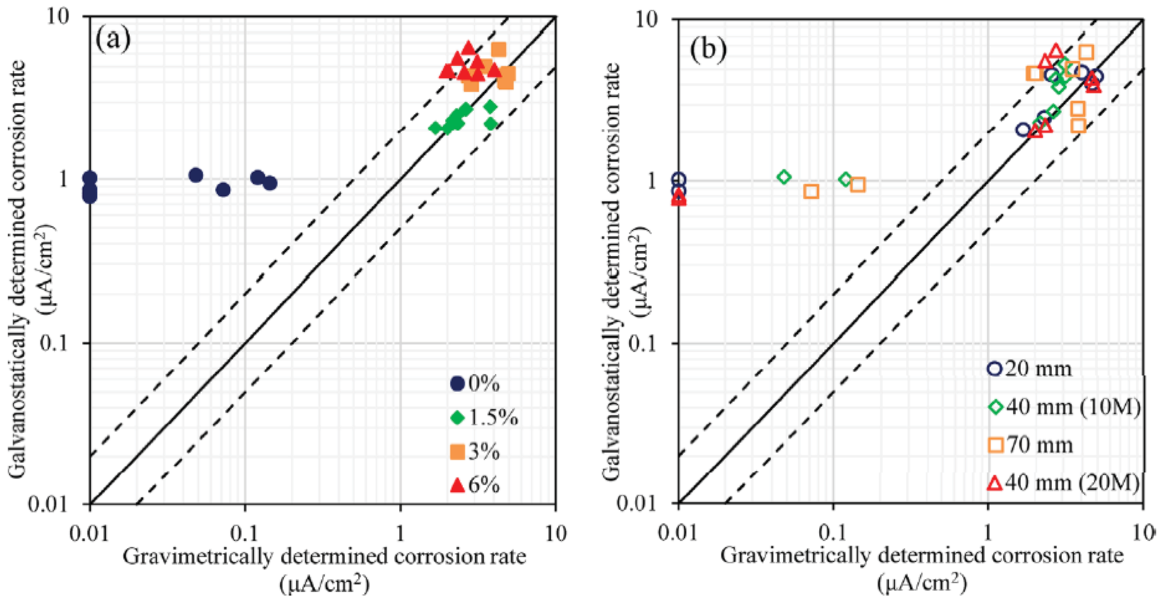

Figure 4 Comparison between the corrosion rate determined through the galvanostatic method and that determined gravimetrically through ASTM G01

In a field study, the device implementing the method was used to inspect the condition of the 70-year-old Cornwall Bridge, located in Kingston, Ontario, Canada. The results obtained by the device were compared to those obtained using traditional bridge-inspection methods such as the half-cell potential method (ASTM C876), chain-dragging (ASTM D4580), visual inspection and resistivity. Figure 5 shows contour plots of the results obtained through the CEPRA method (corrosion rate values) compared to that obtained using the half-cell potential and resistivity methods. In general, the three methods identified similar high-risk zones; namely, in the middle of the investigated zone and in the East zone near both U.S. and Canadian borders. These zones were also observed to suffer extensive rust staining, cracking, spalling and delamination of the concrete cover; which were attributed to corrosion. All of the areas identified to have a corrosion risk were also found to have extensive damage when evaluated using the chain-dragging method (ASTM D4580), which is typically used for these applications. The results presented for the 36 m × 6 m investigated area (including data collection and plotting, which are done automatically) were obtained in less than 4 hours using the commercial device, which is capable of determining the corrosion rate and resistivity simultaneously, as well as the half-cell potential if a connection to the rebar is established. This is a significant time reduction compared to the traditional time-consuming measurements that require establishing a connection to the rebar network.

Other experimental and numerical work done on the CEPRA method, by several other researchers and inspection agencies, can be requested from the author of this nomination form.

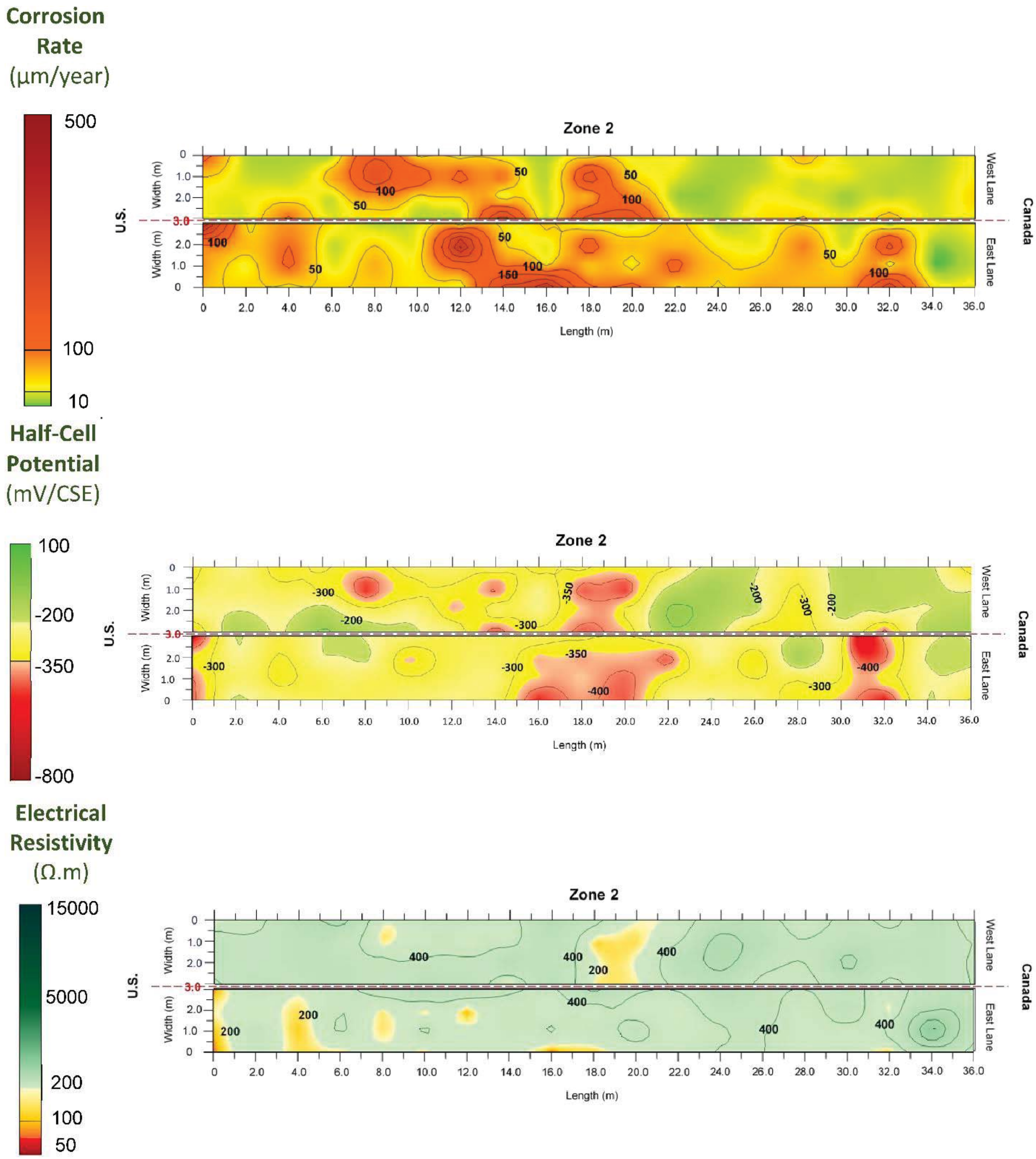

Figure 5 Contour plots of the corrosion rate obtained through the CEPRA method compared to resistivity and half-cell potential results

5. How can the innovation be incorporated into existing corrosion prevention and control activities and how does it benefit the industry/industries it serves (i.e., does it provide a cost

and/or time savings; improve an inspection, testing, or data collection process; help to extend the service life of assets or corrosion-control systems, etc.)?

The innovation saves significant time during inspection of reinforced concrete elements susceptible to corrosion initiation. The time-savings are due to mitigating the need to damage the concrete cover to establish a connection the reinforcement. Damaging the concrete cover is traditionally done several times depending on the size of the area under inspection and the connectivity of the reinforcement network. Since the concrete cover is not damaged while performing the measurement, the need for repair/patching materials is also mitigated. Mitigating the need for connection also allows investigating corrosion for critical structures where damaging the concrete is not allowed (such as nuclear power structures).

Since the CEPRA method can perform corrosion rate measurements in under 10 seconds per measurement, it also allows significant time savings compared to other time-consuming measurements. Furthermore, the data collected during inspection are transferred, through Bluetooth®, from the measurement device to the user's tablet, and the tablet displays the final results as well as contour plots of the corrosion rate and concrete resitivity for the area under consideration. This enables additional saving time in data collection, interpretation and results' plotting. The time and, hence, cost savings associated with the method enables consulting/inspection agencies to perform more frequent corrosion monitoring work, which is expected to lead to more timely repair/rehabilitation strategies and service-life extension for structures susceptible to corrosion.

6. Is the innovation commercially available? If yes, how long has it been utilized? If not, what is the next step in making the innovation commercially available? What are the challenges, if any, that may affect further development or use of this innovation and how could they be overcome?

The device implementing the CEPRA method has been commercialized by Giatec Scientific Inc. under the name iCOR®. The device enables the user to measure the corrosion rate, concrete resistivity and the half-cell potential simultaneously (note that the half-cell potential is measured only if a connection to the rebar is established). The device has been successfully used by consulting/inspection agencies, in several countries (e.g. Canada, USA, Japan, Norway and Switzerland, Australia, Chile, Hong Kong, China) and by several universities in Canada, USA, Switzerland and Norway for the past two years. Examples of notable structures where the device was used include:

- The confederation bridge: Prince Edward Island, Canada
- 3rd Avenue Bridge: Minnesota, USA

- John Coffee Memorial Bridge: Alabama, USA
- Three Nations Bridge Crossing: Ontario, Canada
- LaSalle Causeway: Ontario, Canada

7. Are there any patents related to this work? If yes, please provide the patent title, number, and inventor.

A list of the patents related to this work can be found in the following table:

Patent Number	Patent Title	Inventors
US: 15/958,481	METHOD AND SYSTEMS RELATING TO CONSTRUCTION MATERIAL ASSESSMENT	Pouria Ghods, Rouhollah Alizadeh, Mustafa Salehi, Sarah Decarufel, Andrew Fahim
PCT: 2948912	ELECTRICAL METHODS AND SYSTEMS FOR CONCRETE TESTING	Rouhollah Alizadeh, Pouria Ghods, Amir Hosein Ghods, Mustafa Salehi
EP: 15792644.5	ELECTRICAL METHODS AND SYSTEMS FOR CONCRETE TESTING	Rouhollah Alizadeh, Pouria Ghods, Amir Hosein Ghods, Mustafa Salehi
US: 15/311,055	ELECTRICAL METHODS AND SYSTEMS FOR CONCRETE TESTING	Rouhollah Alizadeh, Pouria Ghods, Amir Hosein Ghods, Mustafa Salehi