Assessing Corrosion of Reinforcing Steel

Lessons learned from select examples

by Andrew Fahim, Pouria Ghods, Aali R. Alizadeh, and Sarah Decarufel

Corrosion of reinforcing steel is the leading cause of concrete deterioration in North America and many other parts of the world.[1] Normally, the corrosion rate of steel in concrete is limited by the high pH (> 12.6) provided by the concrete pore solution, which promotes the formation of a passive oxide layer on the reinforcement surface. However, active corrosion can initiate if pH-reducing reactions such as carbonation occur or if the reinforcement surface is exposed to chloride contents higher than a certain critical threshold. Corrosion propagation results in reaction products that occupy volumes greater than the original bars, and this leads to concrete cover cracking, spalling, and delamination.[2] Following corrosion initiation, it is crucial to accurately determine the rate at which corrosion is propagating and the extent of the areas suffering corrosion to assess the type, urgency, and location of the required repair and rehabilitation.

Several methods have been used for corrosion detection and evaluation. These can range from simple visual observations or chain-dragging to electrochemical corrosion monitoring. This article presents two case studies in which we have used multiple methods for corrosion assessment. The aim is to introduce the capabilities and limitations of these methods and to describe how they can be synergistically used to achieve a more complete picture of the degradation mechanisms in reinforced concrete structures.

Corrosion Evaluation Methods

Visual and acoustic

The traditional corrosion detection method is visual inspection for rust stains or spalling and delamination of the concrete cover. Although this is, certainly, the simplest and least expensive option for detecting corrosion, it has a major drawback—the observer can detect corrosion signs only after corrosion has propagated significantly enough to damage the surrounding concrete. At this stage, repairs are rather costly and time-consuming to implement, since the concrete cover has already suffered an appreciable extent of damage.

Other traditional methods include hammer sounding and chain-dragging (ASTM D4580/D4580M, “Standard Practice for Measuring Delaminations in Concrete Bridge Decks by Sounding”), in which the acoustic response of the concrete cover to hammer impact or a dragged chain is evaluated to detect delamination. ASTM D4580/D4580M notes that hammers or chains provide a clear ringing (high frequency) sound over nondelaminated concrete and a dull or hollow (low frequency) sound when delaminated concrete is encountered. Although these methods allow detection of internal cracking before external signs are apparent, they are only applicable after sufficient corrosion products have formed for cracking and delamination to occur. Acoustic methods also provide no information regarding degradation mechanisms.

Electrochemical

Because corrosion is an electrochemical process, electrochemical methods are the most theoretically sound methods of monitoring corrosion and determining its propagation rate. The most widely used electrochemical method for corrosion assessment is the corrosion potential method (ASTM C876, “Standard Test Method for Corrosion Potentials of Uncoated Reinforcing Steel in Concrete”). In this method, a $Cu/CuSO_4$ reference electrode (or another similar half-cell) is connected to the reinforcement through a hole induced in the concrete cover and the potential difference between the reference electrode and the reinforcing bars is recorded via a voltmeter. Through moving the half-cell over the concrete cover, different potentials are recorded, indicating

Table 1:
Summary of evaluation criteria for corrosion potential, corrosion rate, and electrical resistivity methods

Corrosion potential method		Corrosion rate method		Resistivity method	
Potential versus $Cu/CuSO_4$, mV	Corrosion probability	Corrosion rate, μA/cm^2	Corrosion state	Resistivity, ohm·m	Corrosion state
> –200	< 10%	< 1	Low	> 20	Low
–200 to –350	Uncertain	1 to 3	Moderate	10 to 20	Moderate
< –350	> 90%	3 to 10	High	5 to 10	High
—	—	> 10	Severe	< 5	Severe

different corrosion states (or different anodic dissolution states). The obtained potential is then used in conjunction with criteria listed in ASTM C876 to determine the risk of corrosion. This method is rather simple. However, there are drawbacks because the method:

- Results in localized damage to the cover to allow connection to the reinforcement;
- Is generally qualitative and does not provide information on the rate of corrosion propagation; and
- Is affected by variables such as cover depth, extent of saturation and oxygen availability, concrete resistivity, and anode-to-cathode ratios within the reinforcing network.[3,4]

The rate of corrosion propagation can be determined using electrochemical corrosion rate measurements. In this process, a surface-mounted device is used to apply a polarizing current ΔI. The shift in potential ΔV is measured and the polarization resistance R_p is determined using $R_p = \Delta V/\Delta I$. The corrosion current density (or corrosion rate) can then be found from the polarization resistance through the Stern-Geary equation $i_{corr} = B/(AR_p)$, where B is the Tafel constant (typically assumed to be 26 mV) and A is the bar area polarized by the applied current.

The traditional method of determining corrosion rate involves inducing a hole in the concrete cover from which a connection with the bar network can be established. This is necessary in determining the shift in the bar corrosion potential. This connection requirement, however, was overcome in the past few years through the introduction of the connectionless electrical pulse response analysis (CEPRA) concept, in which corrosion rate measurements can be obtained without the need for bar connection through a Wenner-probe setup, similar to that used for determining concrete resistivity.[5,6]

The electrical resistivity method is also widely used to assess concrete quality, thereby determining the risk of corrosion. The resistivity method determines the concrete resistance to the propagation of a high-frequency AC current (>1 kHz), determined through the Wenner array probe setup.[7] The concrete resistivity is a direct measure of its porosity and pore-structure connectivity and tortuosity. Because porosity directly relates to concrete permeability and to the ionic transfer between anodes and cathodes formed over the bar during corrosion, this method can be used to indirectly estimate the risk of corrosion and its rate of propagation.

To determine the corrosion potential, corrosion rate, and concrete resistivity, a commercial device capable of simultaneously performing the three measurements is used in the presented case studies. Table 1 provides a summary of the criteria used to deduce the risk of corrosion from results of these test methods.

Case Studies

The first case study is for the Three Nations Bridge Crossing located in Cornwall, ON, Canada. The south channel bridge is one of the many bridges crossing the U.S. and Canada border. The south channel bridge crosses the Saint Lawrence River and connects Cornwall Island, ON, with the State of New York. The bridge carries the Akwesanse International Road with traffic of about 2 million vehicles per year. The bridge is a high-level suspension bridge that straddles the waterway used by large ocean-going ships navigating the Saint Lawrence Seaway. This bridge opened to traffic in December 1958. The bridge evaluation work included visual inspection and chain-dragging as well as corrosion potential, corrosion rate, and electrical resistivity measurements. Figure 1 shows the location of the bridge and electrochemical measurements performed on the bridge deck using the commercial handheld device.

The second case study is for the LaSalle Causeway, located in Kingston, ON, Canada. The causeway provides an important link within Kingston across the Cataraqui River, between downtown Kingston and the Barriefield/Canadian Forces Base (CFB) area. About 23,000 vehicles cross the causeway every day. The causeway consists of five interconnecting structures: the East Bridge, the East Wharf, the Bascule Bridge, the West Wharf, and the West Bridge. The East Bridge, presented in this study, opened to traffic in 1917, and the original single span through truss bridge was replaced by the current structure in 1969. Figure 2 shows the location of the East Bridge and photographs of measurements being taken on the underside of the deck. Although detailed testing was performed for the entire East Bridge, including the abutments and the pier, the presented results focus on the underside of the bridge deck. The evaluation work included visual inspection, hammer sounding, corrosion potential, and corrosion rate measurements.

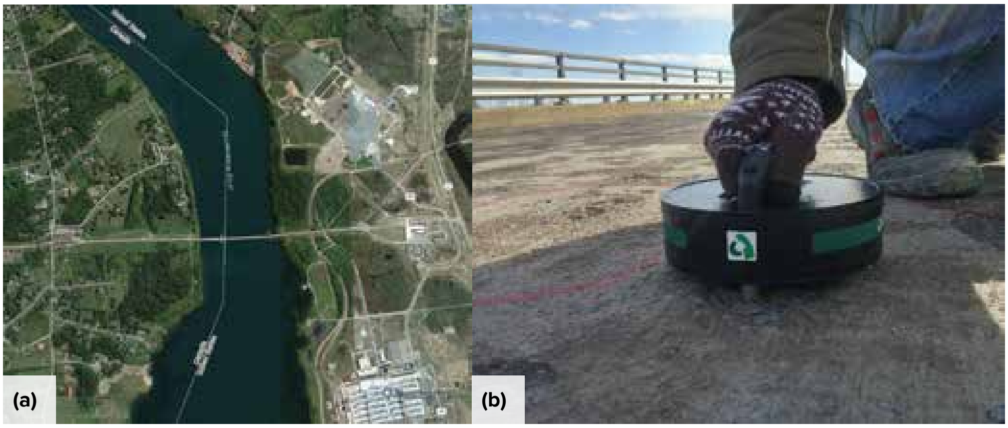

Fig. 1: The Three Nations Bridge was evaluated using visual, acoustic, and electrochemical measurements: (a) aerial view of Cornwall Island, ON, Canada (left) and Akwesasne, NY (right); and (b) closeup of the device used to take electrochemical measurements

Fig. 2: The LaSalle Causeway was evaluated using visual, acoustic, and electrochemical measurements: (a) aerial view of downtown Kingston, ON, Canada (left) and Barriefield/CFB (right); and (b) a view of the platform used to inspect the deck soffit

Three Nations Bridge

Figure 3 shows an example of severe cracking observed on the bridge deck after the removal of the asphalt wearing layer. Similar damage was visually observed throughout the full span area, albeit to different extents. Damage ranged from minor cracks to severe spalling.

Figure 4 shows a summary of the delaminated zones identified by both the visual inspection and chain-dragging methods. The results showed distributed damage throughout the full presented zone in localized areas. It should be noted, however, that portions of the visually observed delaminations and cracks were attributed to freezing-and-thawing and salt-scaling damage and not specifically to corrosion propagation.

Figure 5 shows resistivity, corrosion potential, and corrosion rate results. In general, both corrosion rate and corrosion potential tests identified similar high-risk zones—namely, in the middle of the investigated zone and in the East zone near both U.S. and Canadian sides. The resistivity values recorded were generally in the range of 100 to 500 ohm·m, which, according to Table 1, indicates a low risk of corrosion. However, it is well-established that resistivity is significantly influenced by the concrete moisture content during investigation. Therefore, these results are attributed to the dry

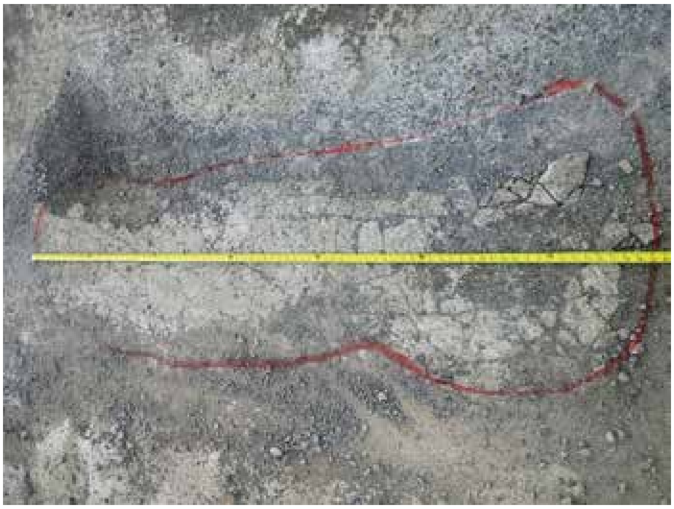

Fig. 3: An example of a damaged area on the Three Nations Bridge

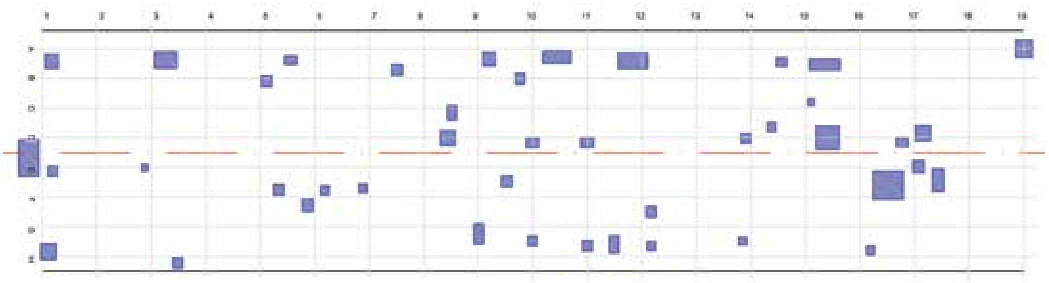

Fig. 4: Delamination zones (in blue) on the Three Nations Bridge identified by visual inspection and chain-dragging

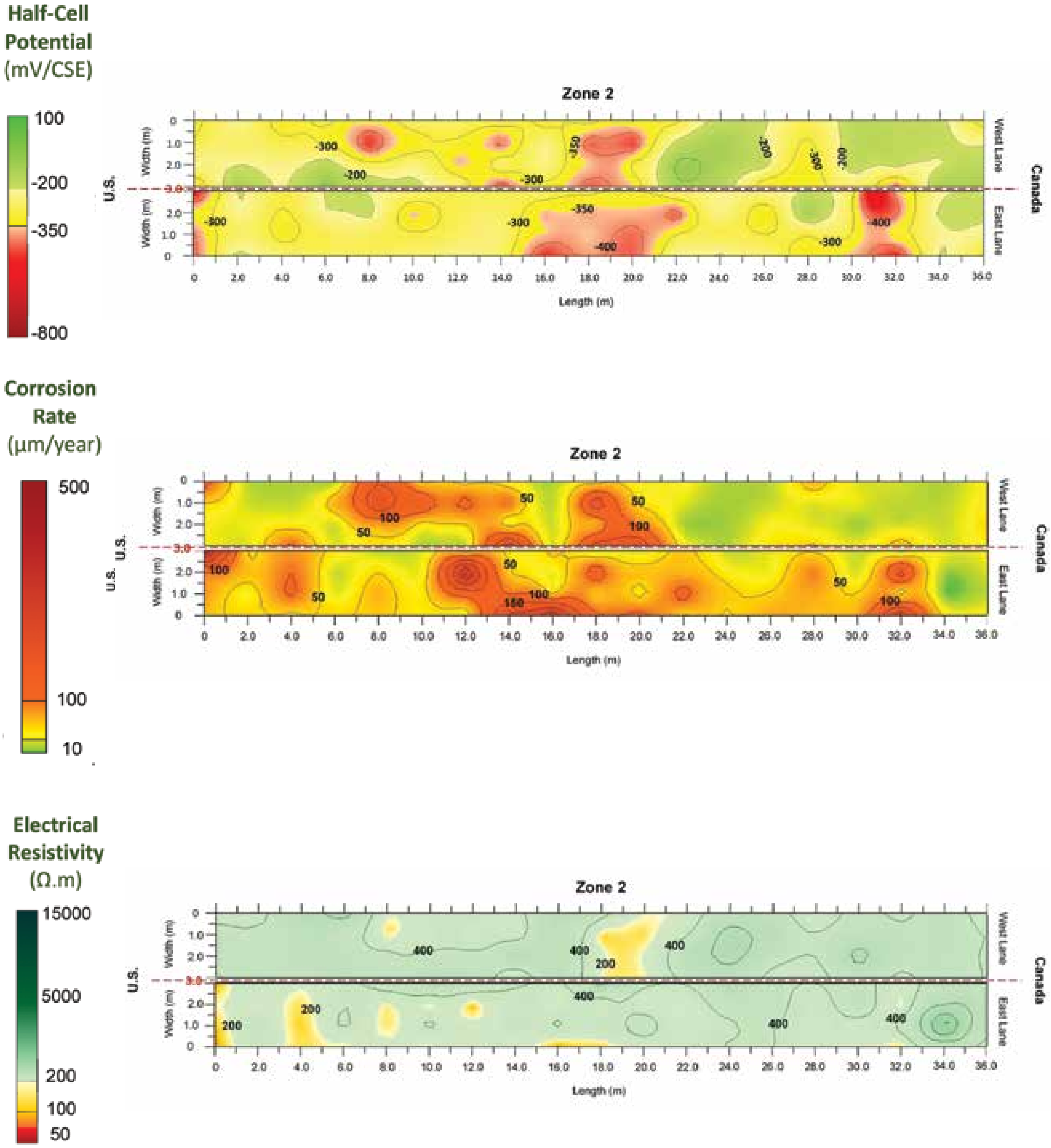

Fig. 5: Corrosion potential, corrosion rate, and electrical resistivity contour maps of the Three Nations Bridge

condition of the slab during the inspection. Nevertheless, the resistivity measurements were still able to detect anomalies (lower resistivity values) in the middle of the investigated zone and in the East lane near the U.S. border. This is in general agreement with the half-cell and corrosion rate results and is attributed to internal cracking or delamination caused by corrosion propagation.

The areas observed to be damaged by the visual inspection and chain-dragging methods were also identified by the combination of half-cell and corrosion rate monitoring. However, it should be noted that the inherent differences between these methods make them useful when applied in conjunction with each other. The chain-dragging and visual observation methods are only able to detect damage when sufficient corrosion propagation has occurred for corrosion to manifest itself. In contrast, the corrosion rate, corrosion potential, and resistivity methods provide information on the state of corrosion at the time of the measurement, even if corrosion has not propagated enough to cause sufficient damage to be visually or acoustically observable. This explains the greater area portions determined to be damaged through electrochemical methods (40 to 60% of the span surface area) when compared to visual and acoustic methods. It is expected that the areas with corrosion activity (determined electrochemically) will show signs of corrosion damage in the future.

It should also be noted that the electrochemical methods allow differentiation between areas degrading solely due to corrosion and those suffering damage due to deicing salt scaling or freezing and thawing (these are the minor areas found to be degrading [refer to Fig. 4] and were not found to have a corrosion activity). This information can be used to determine appropriate rehabilitation methods based on the cause of the damage. Furthermore, since corrosion rate measurements provide quantitative information regarding the rate of propagation, the urgency of repair can be determined and the time to cracking can be estimated.

Fig. 6: The underside of the LaSalle Causeway bridge deck exhibited visible damage only near the central pier

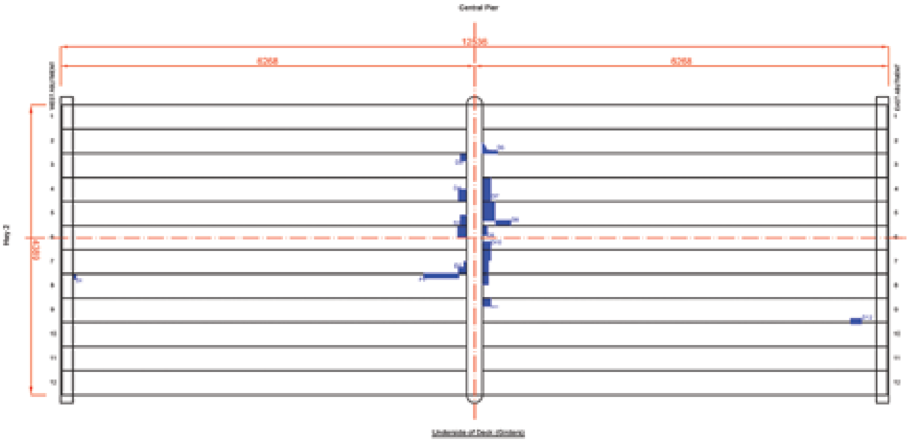

Fig. 7: Delamination zones (in blue) on the LaSalle Causeway bridge were identified through visual inspection and hammer sounding

LaSalle Causeway

Figure 6 shows the underside of the LaSalle Causeway bridge. It can be observed that the girders are in good condition with damage observed only near the central pier. Figure 7 shows the results of the visual inspection and hammer sounding survey on the bridge. The survey showed significant damage due to corrosion at the area near the central pier, where delamination, cracking, and rust staining were found visually and via hammer sounding. The higher damage observed in this area is primarily attributed to the seepage of salt-laden water (from deicing salts) through the joint over the central pier. No damage was observed in the area between the central pier and the two abutments.

Figure 8 shows corrosion potential and corrosion rate contour plots for the underside of the bridge deck. The results from both methods agree with the visual inspection and show that the vicinity of the central pier is exhibiting significant damage as observed with the low corrosion potentials and the high corrosion rates. However, these methods also showed evident corrosion activity in girders 1, 2, 4, 11, and 12, and lower activity for the other girders. This corrosion activity was not observed visually, or by hammer sounding (refer to Fig. 6). This demonstrates the value of these methods in cases where corrosion has not yet led to concrete degradation. The results can act as an early alert for stakeholders, notifying them that these girders will eventually show some damage and allowing them to put into place early mitigation measures before concrete spalling or delamination occur. Such early detection of the susceptibility of members to corrosion damage cannot be done without the use of electrochemical techniques.

Conclusions

Visual inspection or delamination detection methods cannot detect corrosion initiation or early stage propagation, as these methods require some extent of damage to occur to the concrete cover. These methods also do not allow inspectors to differentiate between areas degrading due to corrosion from areas suffering other deterioration issues.

A combination of corrosion potential, corrosion rate, and electrical resistivity testing can provide information on the location of the damage and the expected consequences of

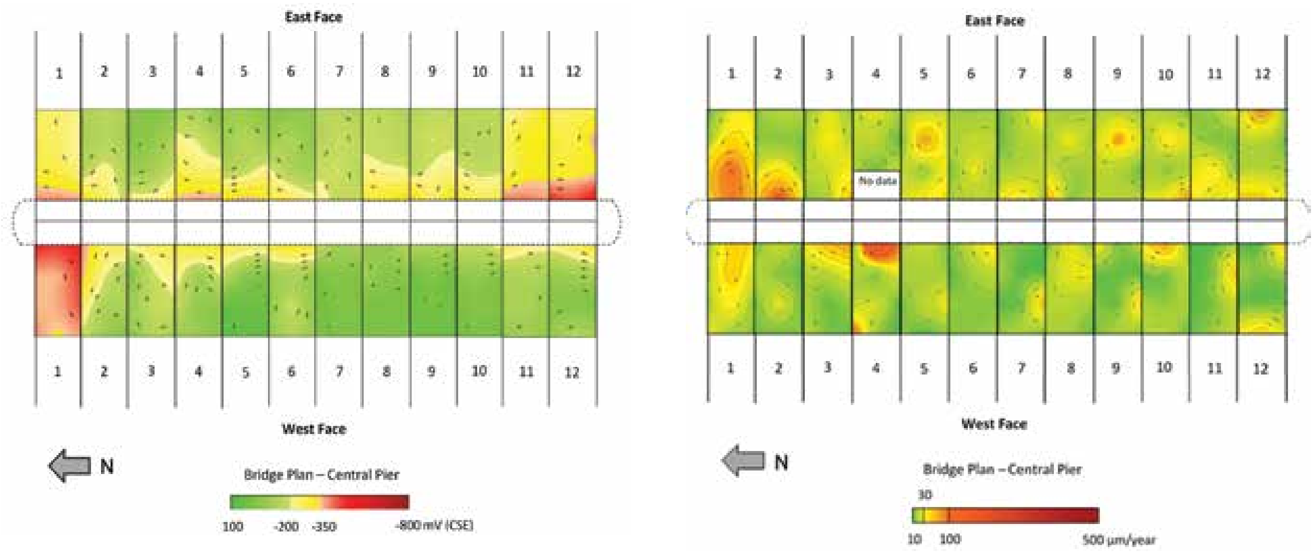

Fig. 8: Corrosion potential and corrosion rate contour maps of the LaSalle Causeway bridge

corrosion propagation. These methods generally provide an earlier alert, before corrosion can manifest and cause significant degradation. They have been shown to be very effective when used in conjunction with each other and provide multiple points of view of concrete degradation, as shown in the presented case studies. Recent advances in commercial devices that can perform these measurements rapidly and simultaneously, while automatically collecting data and generating contour maps, can save significant time for inspectors and provide more information than the traditional inspection methods.

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