

# Combination of Impressed Current and Galvanic Cathodic Protection System for Bridge Deck Corrosion Mitigation

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## Abstract

The Fifth Street Bridge located in Courtenay, British Columbia was constructed in the 1960s and consists of a steel truss frame and reinforced deck supported by steel girders and two abutments. The deck reinforcement was corroding due to exposure to deicing salts. However, it could not be easily replaced as the top flanges of the supporting steel girders were embedded in the bottom half of the bridge deck. As part of the rehabilitation, the City of Courtenay, the bridge owner, requested the design and installation of an impressed current cathodic protection (ICCP) system to protect the reinforcement in the deck. Due to the presence of embedded beam flanges, the contractor was concerned about the risk of shorting the ICCP system to the embedded beam flanges, which would make the ICCP system inoperable. To address these concerns, a combination of impressed current and galvanic systems was used on this project. The ICCP system was designed and installed in the top of the deck to protect the rebar and a targeted galvanic system consisting of discrete anodes was installed in the deck underside to protect the top flanges of the supporting steel girders embedded in the deck. The system was activated in July 2022 and monitored remotely for 6 months to ensure its continued optimal performance.

## Introduction

The Fifth Street bridge is located in Courtenay, BC and carries the Fifth Street over the Courtenay River. The bridge is a two-lane steel truss structure constructed in the 1960s supported by steel I-beam girders and reinforced concrete abutments (Figure 1). Over time, exposure to deicing salts led to chloride-induced corrosion of both the reinforcement and the embedded top flanges of the steel girders. The deck could not be easily replaced due to the presence of embedded girders, so the City of Courtenay, the bridge owner, requested the design and installation of an impressed current cathodic protection (ICCP) system to protect the reinforcement in the deck from corrosion.

Cathodic protection (CP) has been shown to be a very effective method of mitigating reinforcement corrosion by providing external current to the reinforcement, which causes the anodic sites to polarize thereby mitigating corrosion. ICCP systems use an external power source, such as AC power, and inert anodes to polarize the steel. A review of different CP systems can be found in Byrne et al. [2] and Goyal et al. [3]. ICCP systems can provide a high current density to quickly polarize the reinforcement in severe environments, but they have to remain isolated from the reinforcement to be functional. Galvanic CP (GCP) systems use sacrificial anodes that are less noble than steel. These anodes will sacrificially corrode which in turn produces CP current to protect the steel. Zinc is the metal typically used for galvanic anodes embedded in concrete. Unlike ICCP systems, galvanic anodes can be directly connected to the reinforcing steel, or they can be isolated from the reinforcement for monitoring.

The contractor who was awarded the rehabilitation project was concerned about the risk of shorting the ICCP system to the embedded beam flanges, which would make the ICCP system inoperable. To address these concerns, an impressed current and galvanic system combination was designed for this project.

## Pre-Design Corrosion Assessment

Before proceeding with CP design, a corrosion assessment was performed to collect the data needed for design calculations, which included electrical continuity testing, corrosion potential survey, and concrete chloride concentration testing.

### Electrical Continuity Testing

Electrical continuity of the reinforcing is necessary for collecting corrosion potential measurements and for CP system installation. ACI 222R-19<sup>1</sup> specifies that if the potential difference between the reinforcing elements is less than 1 mV or if the resistance is less than 1 Ohm, then the reinforcing steel is deemed electrically continuous. In most cast-in-place reinforced concrete structures conventional reinforcement is electrically continuous due to the crossing of bars and tie wires. If the reinforcement is found to be electrically isolated, then continuity bonds must be installed prior for the implementation of cathodic protection. Generally, reinforcement within each lane of the bridge was found to be electrically continuous, although some locations of discontinuous reinforcement were identified that required installation of continuity bonds during the construction phase. However, reinforcement within each lane was electrically isolated from the reinforcement in the other lane and was electrically isolated from the steel I-beam girders.

### Corrosion Potential Measurements

Corrosion potential measurements, also referred to as half cell potential measurements, were collected per ASTM C876<sup>2</sup> *Standard Test Method for Corrosion Potentials of Uncoated Reinforcing Steel in*

*Concrete* to identify areas at high probability of active corrosion. Corrosion potential measurements in the deck were collected on the top of the deck on a 500 mm by 500 mm grid using a copper/copper sulfate (CSE) reference electrode. In the I-beams, the measurements were collected along the underside of the beam at a spacing of 250 mm. ASTM C876<sup>2</sup> provides a generally accepted interpretation of normalized CSE measurements (Table 1). It should be noted that the interpretation values provided in ASTM C876 are a general guideline based on values normalized to 22°C and are not absolute values. The threshold values can shift based on the concentration of moisture and oxygen in the concrete, concrete resistivity, as well as other environmental factors like temperature.

Generally, most of the corrosion potential measurements were in the range of 90% probability of passive reinforcement, although some areas in the uncertain range and in the 90% probability of active corrosion were observed in the top of the deck and along the embedded I-beams in the deck underside (Figure 2 and Figure 3). It is not unusual for corrosion potential testing to show measurements in the range of 90% probability of passive steel, even in areas of active corrosion. This can happen when the concrete resistivity is quite high, which affects the interpretation of the corrosion potential data.

To better assess the probability of corrosion in the deck, relative change in potential between adjacent measurements were plotted for the deck. When corrosion occurs, there is a potential difference between the anodic and cathodic regions of the corrosion cell. Anodic and cathodic regions throughout a structure will be near to each other and have varying potentials that create potential gradients between adjacent points. A large potential difference between two locations indicates a high probability of active corrosion. Potential difference plots for the top of the deck and the deck underside are presented in Figure 4 and Figure 5, respectively. It is clear that despite low corrosion potential values recorded for most of the deck and I-beams, there are still areas with a high probability of active corrosion in some areas as indicated by the large difference in potential between adjacent measurements.

### **Chloride Concentration Testing**

In addition, a total of 20 cores, from each lane, were collected for chloride concentration testing, which was performed in accordance with ASTM C1152<sup>3</sup> *Standard Test Method for Acid-Soluble Chloride in Mortar and Concrete*. Chloride concentrations in 80% of the cores were above the corrosion initiation threshold at rebar depth. Comparing this to the corrosion potential and potential difference plots indicates that the corrosion is in the early states of propagation. Now is the perfect time to install a CP system to mitigate corrosion before it causes wide-spread concrete damage.

## **CP System Design and Installation**

### **Cathodic Protection Criteria**

All cathodic protection standards use criteria that is based on measuring potentials that are free from the influence of the IR drop and measuring polarization. When current is flowing between the anodes and the structure there is a voltage drop (IR drop) that occurs in the electrolyte (concrete pore solution). To understand if the structure is receiving the proper amount of current, the IR drop must be calculated or removed from the potential measurement. The IR drop is removed from the potential measurement by disconnecting the anode from the reinforcement and recording the potential within the first 0.1 and 1.0 seconds, called the "Instantaneous OFF" potential.

Polarization is a change in potential caused by changes in the chemistry at the structure (reinforcing steel) to electrolyte (concrete) interface. When current transfers from an electrolyte to a metal (i.e., concrete to steel), a reduction reaction occurs. The cathodic reaction involves the reduction of dissolved oxygen and the creation of hydroxyl ions, which elevates the pH at the surface of the structure, causing a potential shift. The chemical difference at the interface, as measured by the potential, is referred to as polarization. When the CP current is interrupted, the polarization will dissipate similarly to the voltage dissipation of a capacitor but may never reach the original native potential, depending on the environment. After disconnecting the anode current from the structure, the potential of the reinforcement is monitored to measure the dissipation of the polarization.

This project used two cathodic protection standards as guidelines for performance assessment and criteria for cathodic protection:

- ICCP System: EN ISO 12696:2016 *Cathodic Protection of Steel in Concrete*, Section 8.3:
  - An "Instantaneous OFF" potential more negative than -720 mV with respect to Ag/AgCl/0.5 M KCl.
  - A potential decay over a maximum of 24 hours of at least 100 mV from "Instantaneous OFF".
  - A potential decay over an extended period (typically 24 hours or longer) of at least 150 mV from the "Instantaneous OFF".
- GCP System: NACE SP0216-2016 *Sacrificial Cathodic Protection of Reinforcing Steel in Atmospherically Exposed Concrete Structures*
  - If the potential of the steel is more negative than -720 mV vs CSE with the sacrificial anode disconnected, then the steel is considered not to be corroding.
  - A minimum of 100 mV of polarization provided the corrosion potential, or decayed off potential, is more negative than -200 mV vs CSE. If the corrosion potential or decayed off-potential is less negative than -200 mV CSE, then the steel is considered passivated, and no minimum polarization is required.

It is important to know that only 1 criterion needs to be met for each system to achieve cathodic protection.

### **ICCP System**

The ICCP system was designed to protect the rebar in the deck. Since an overlay was already planned for the top of the deck, a mixed metal oxide (MMO) mesh anode that can be cast into the overlay was selected as the ICCP anode. It should be noted that this type of ICCP would not have been to protect the embedded I-beams due to their large surface area and depth from the top of the deck. In addition to the mesh anode, the ICCP system included distribution bars, distribution box, and a transformer-rectifier unit. In addition, a remote monitoring unit (RMU) was installed to remotely monitor system performance.

The top of the deck was divided into 2 zones or circuits; zone 1 was dedicated to the westbound lane, and zone 2 to the eastbound lane (Figure 6). This allowed the contractor to maintain 1 lane of traffic across the bridge during construction. Each ICCP zones had 5 access ports and 3 reference electrodes as well as structure, test anode connections. Access ports were drilled in the deck and junction boxes were installed on the deck underside to rout all the wires to the distribution box (Figure 7).

After the top of the deck was removed, the mesh anode was installed in each zone together with distribution bars, reference electrodes and all the ICCP system connections and wiring (Figure 8). All wires were color-coded for ease of identification and individually labeled with their respective IDs (Figure 9). After all the wires were pulled through the access ports into the junction boxes, the overlay concrete was placed on top of the mesh anode (Figure 10). On the deck underside, the ICCP wires were routed from the junction boxes to the distribution box installed at one of the abutments, which was then collected to the RMU and the transformer-rectifier (Figure 11 and Figure 12).

### **GCP System**

A targeted galvanic cathodic protection system was designed to protect the top flanges of the I-beam girders embedded in the bottom of the deck. A targeted approach was selected to protect the steel girders in locations where pre-design corrosion potential testing indicated a high probability of active corrosion and in areas of concern identified by the Engineer of Record (EOR) (Figure 13). Drilled in Type 2A galvanic anodes with a zinc core encased in an alkali-activated mortar were installed on each side of the I-beam girders (Figure 14). The GCP system was divided into 6 zones, with 1 zone per girders. Each zone included smaller grouping of anodes which were referred to as subzones, structure and test connections, 4 reference electrodes and 2 junction boxes.

Prior to anode installation in each subzone, all the reinforcement in this area was located with a ground penetrating radar (GPR) and marked out on the concrete surface. Core holes were then drilled into the concrete from the deck underside avoiding the reinforcing steel and shallow wire chases were cut between the anode holes to accommodate the anode wires (Figure 15). In areas of full-depth deck repairs, removable forms were placed in the bottom of the deck in areas of anode installation to create holes for the anodes to avoid coring into the new concrete (Figure 16). To allow for monitoring of the GCP system, the anodes were not directly connected to the girders. Instead, anode wires, reference electrode wires, structure and test connections were routed to the distribution box at the abutment where anode and structure connection wires were connected through a shunt. Just like the ICCP, the GCP system was then connected to the RMU to allow for remote monitoring of system performance.

### **Monitoring Results**

Immediately after activation of the GCP system, the anodes exhibited a high initial current output. This behavior is typical for galvanic systems because galvanic anodes are self-regulating unlike the ICCP systems where the amount of current is controlled at the rectifier. Newly installed galvanic anodes provide a large amount of current due to low resistivity of the grout surrounding the anodes at early stages. Over the first several weeks, the current output decreased significantly as the grout resistivity increased due to cement hydration and the steel began to polarize. After approximately two months of operation, current output from the GCP anodes stabilized at a lower steady-state level, consistent with ongoing polarization of the reinforcing steel and reduction in corrosion activity (Figure 17). Polarization measurements shown as the vertical spikes in the OFF potential data shown in Figure 18 showed that the GCP system was meeting the polarization criterion for CP approximately 3 months after activation.

The ICCP system was closely monitored after activation to determine if it would be necessary to increase the current to either zone. Pushing the anode too hard too quickly can deplete the anode and leave the area unprotected. Constant ICCP over long duration has greater benefit than a quick shot of current for

a short period of time. Polarization measurements of the ICCP system showed that it was also meeting the 100 mV polarization criteria for CP (Figure 19).

## Conclusions

This project successfully demonstrated the application of a combination of an impressed current and galvanic CP systems to achieve an efficient and cost-effective design. An ICCP system was installed in the deck surface to protect the top and bottom layers of reinforcement, while a targeted GCP system was installed at the underside of the deck to protect the embedded steel girder flanges. It was possible to select a targeted approach based on a pre-design corrosion evaluation that identified areas of active corrosion.

The combined use of GCP and ICCP systems provided comprehensive corrosion mitigation, effectively addressing both localized and wide-spread corrosion risks of the girder flanges and the conventional reinforcement in the deck, respectively. Monitoring results confirmed that both systems met the applicable cathodic protection criteria. The addition of remote monitoring provided valuable insight into system performance. The combination CP strategy implemented at the Fifth Street Bridge offers a practical model for corrosion mitigation where embedded steel elements pose challenges for conventional ICCP systems.

Table 1. ASTM C876 Interpretation of CSE Corrosion Potential Measurements

Corrosion Potential	Probability of Active Corrosion
< -350 mV	90%
- 350 mV to -200 mV	Uncertain
> -200 mV	10%

Figure 1. Fifth Street Bridge



Figure 2. Corrosion Potential Survey Map of the Top of Deck

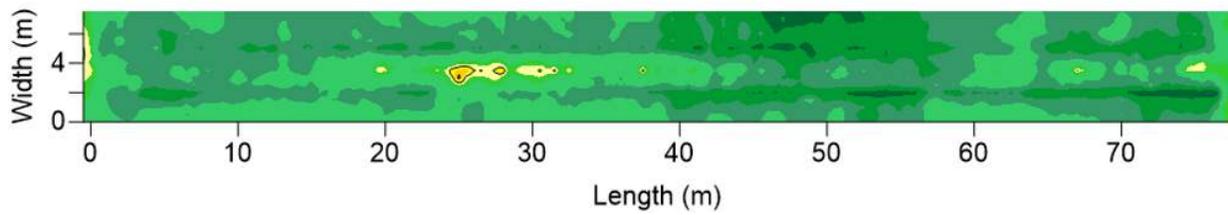


Figure 3. Corrosion Potential Survey Maps of the Deck Underside along the Beams, Typical

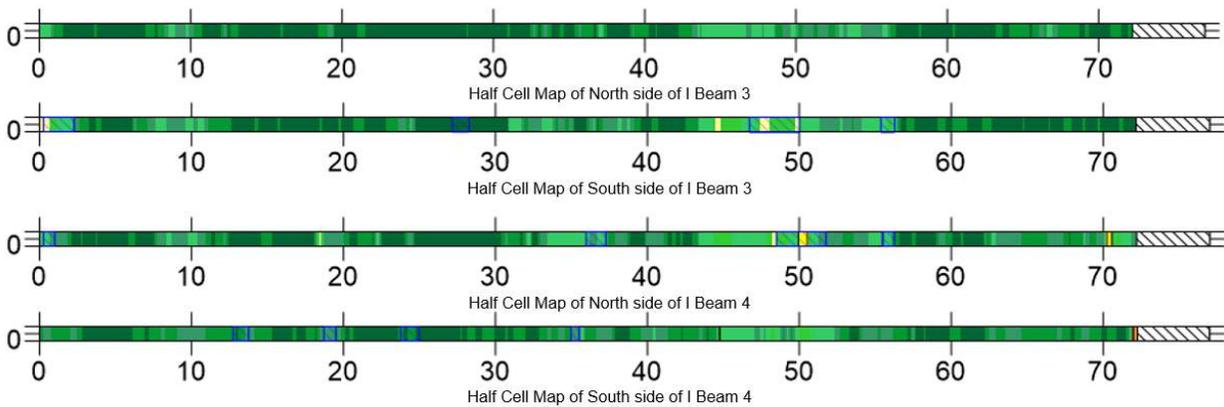


Figure 4. Potential Difference Plot for the Top of Deck

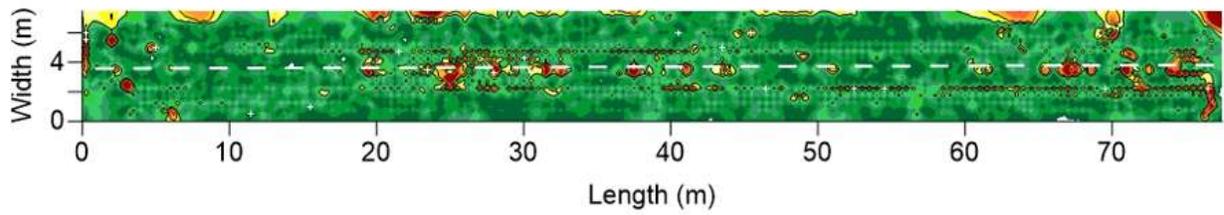


Figure 5. Potential Difference Plot for the Deck Underside along the Beams, Typical

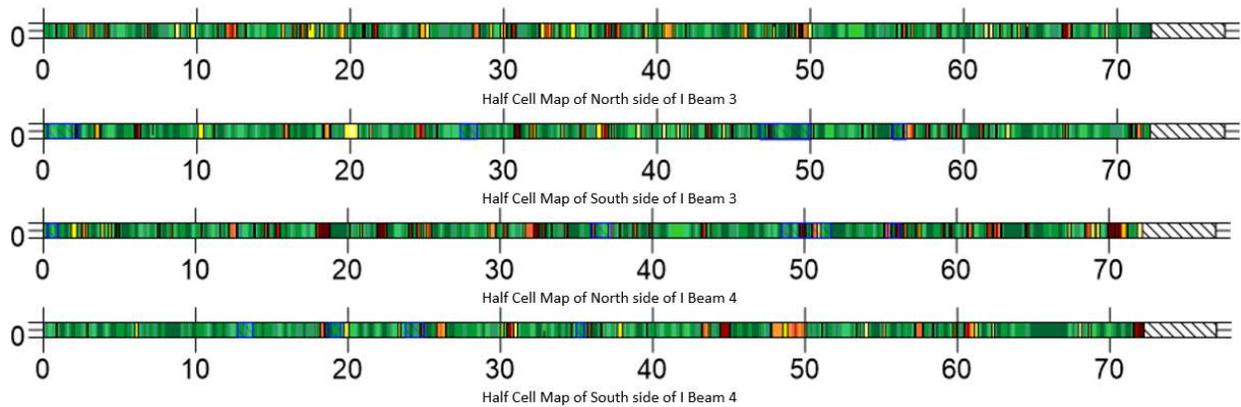


Figure 6. ICCP System Plan View, Top of Deck

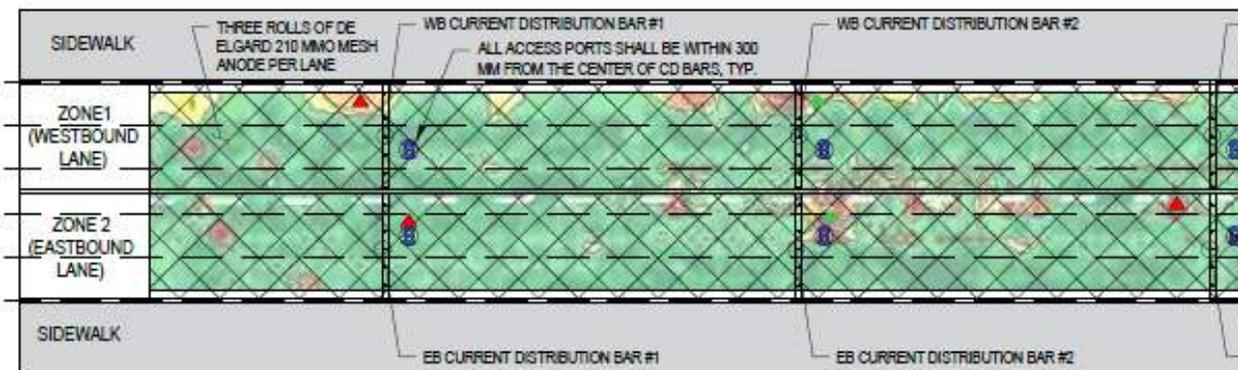


Figure 7. ICCP System Deck Section View

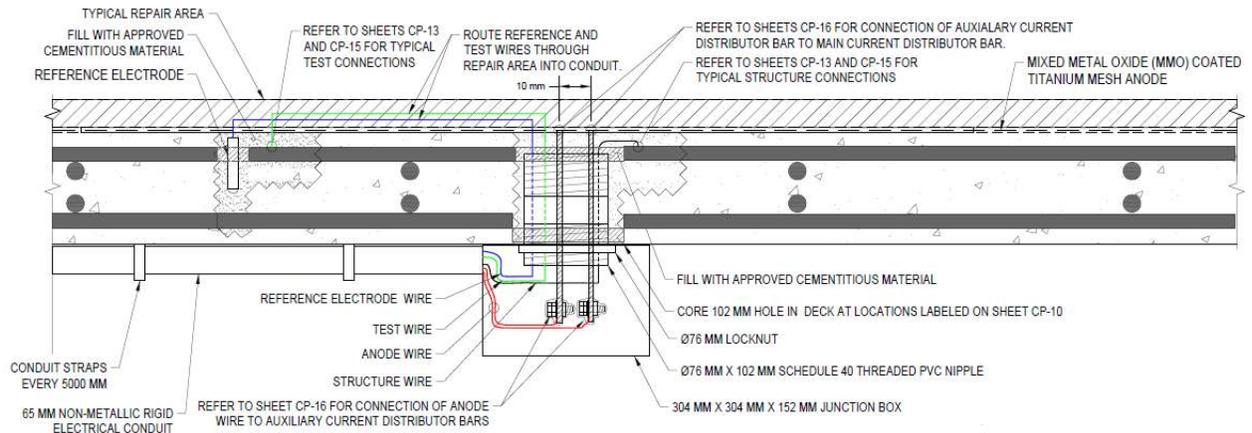


Figure 8. ICCP Anode Placement



Figure 9. Junction Box with ICCP Wiring

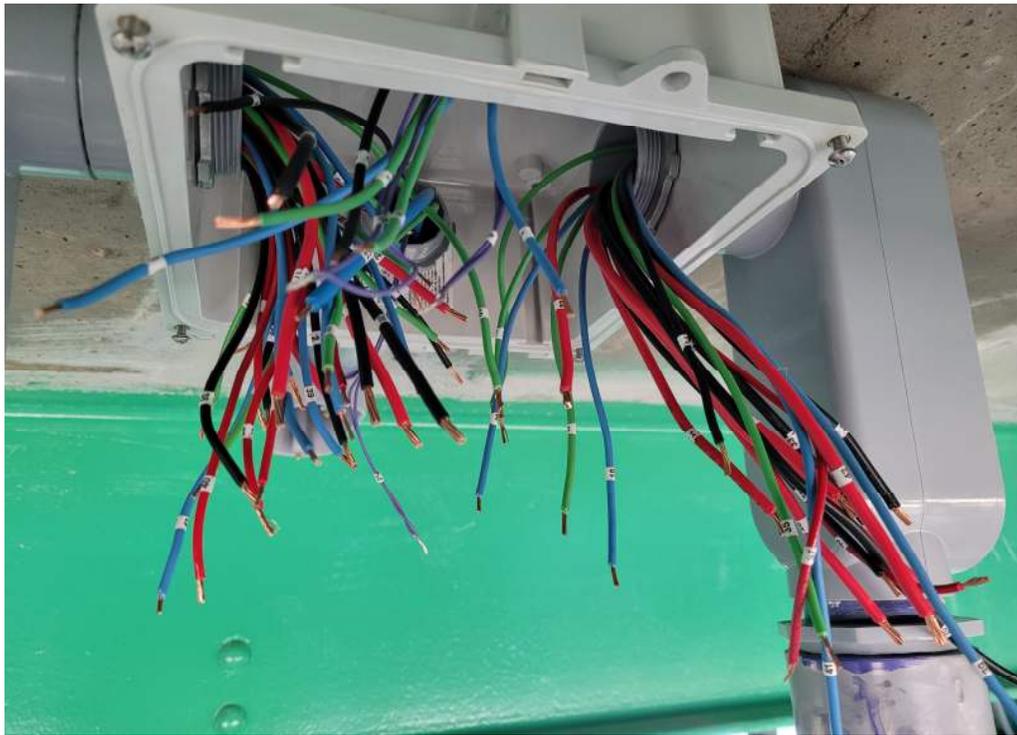


Figure 10. Deck Overlay Placement



Figure 11. ICCP Distribution Box (Left), RMU (Middle) and Transformer-Rectifier (Right)



Figure 12. Completed Installation

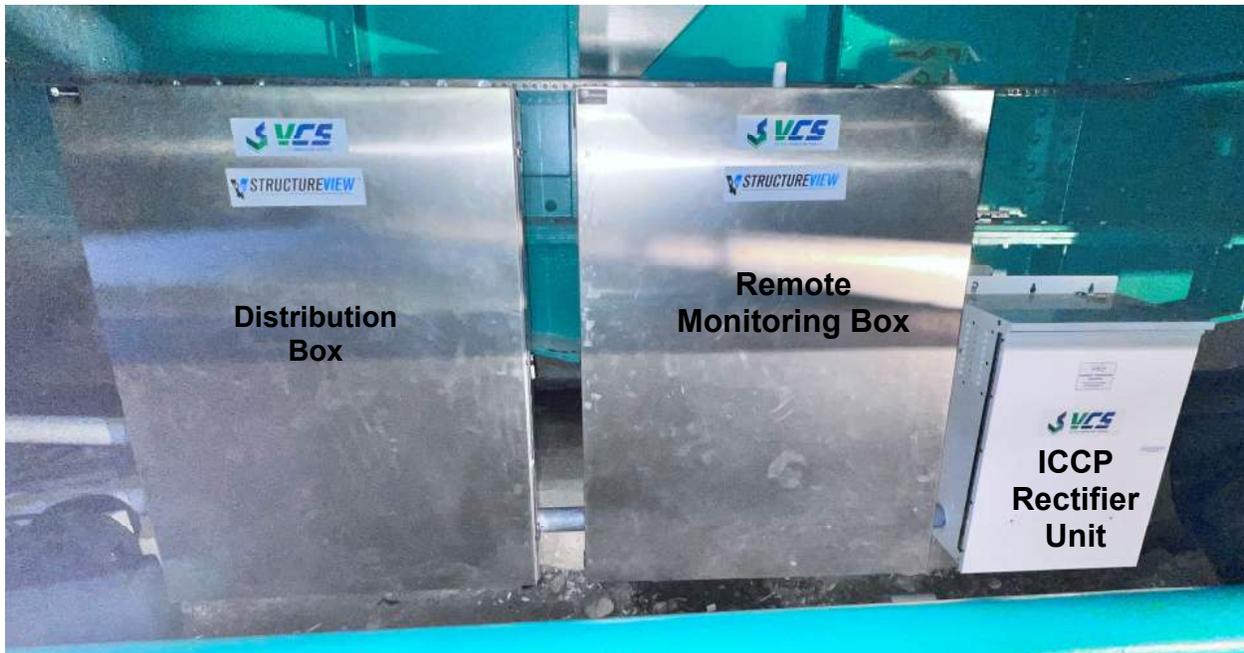


Figure 13. Plan View of the GCP System Installation along 2 I-Beam Girders, Typical

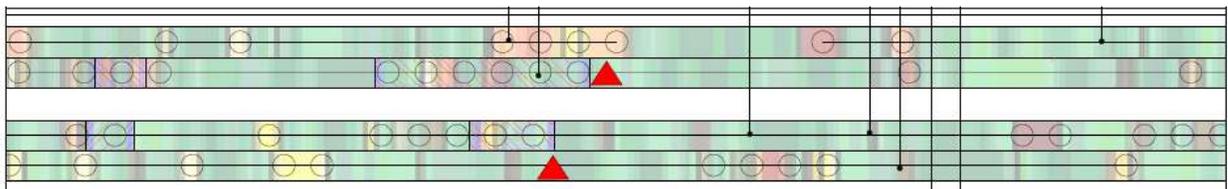


Figure 14. Cross-Section of the Deck Showing Galvanic Anode Installation

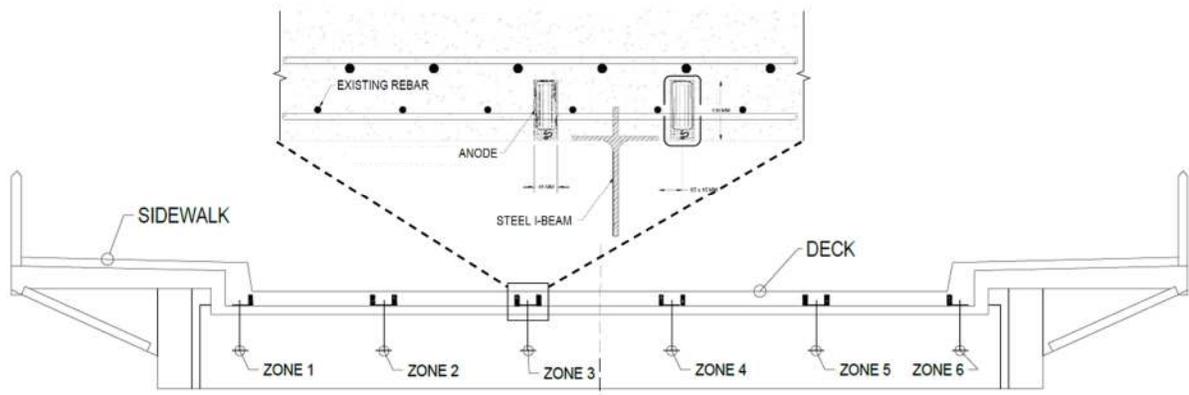


Figure 15. Coring Anode Holes (Left) and Grouted Anode Connected to a Red Anode Wire (Right)

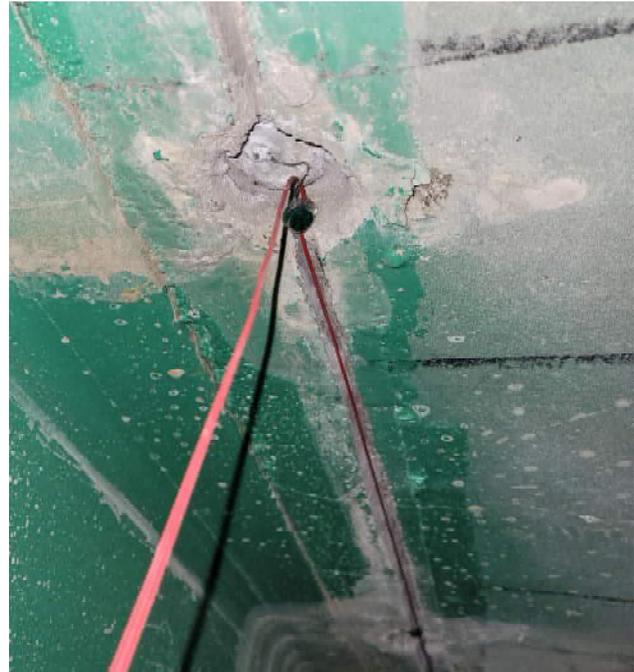


Figure 16. Full-Depth Deck Repair with Removable Forms for Anode Holes



Figure 17. Current Output of the GCP System

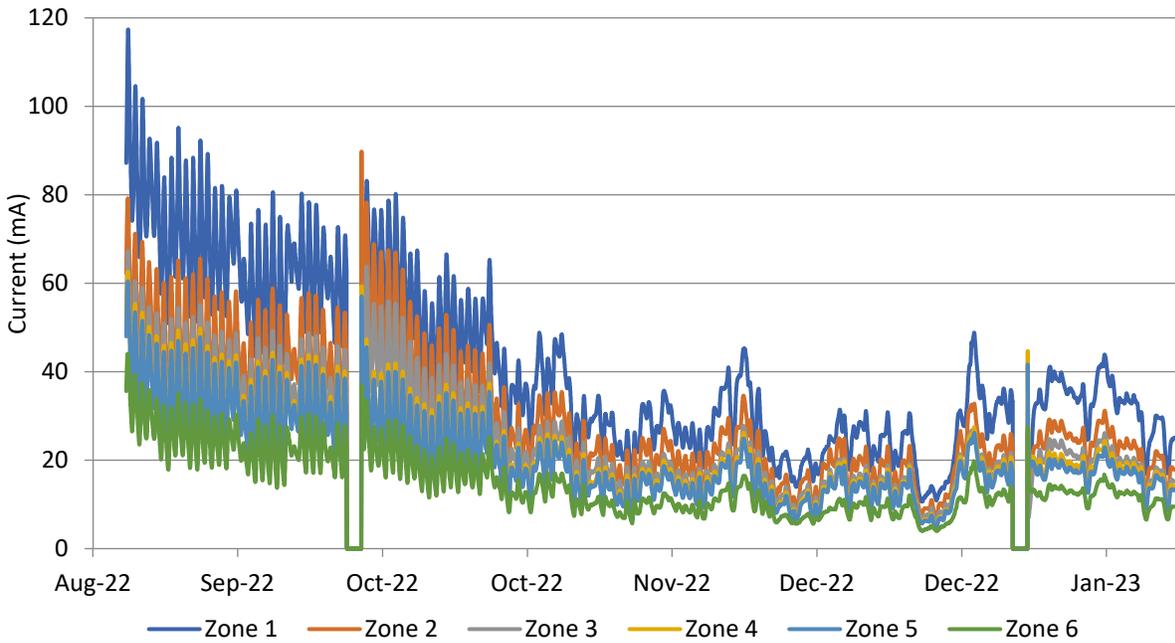


Figure 18. OFF Potential Measurements for Zone 2 of the GCP System

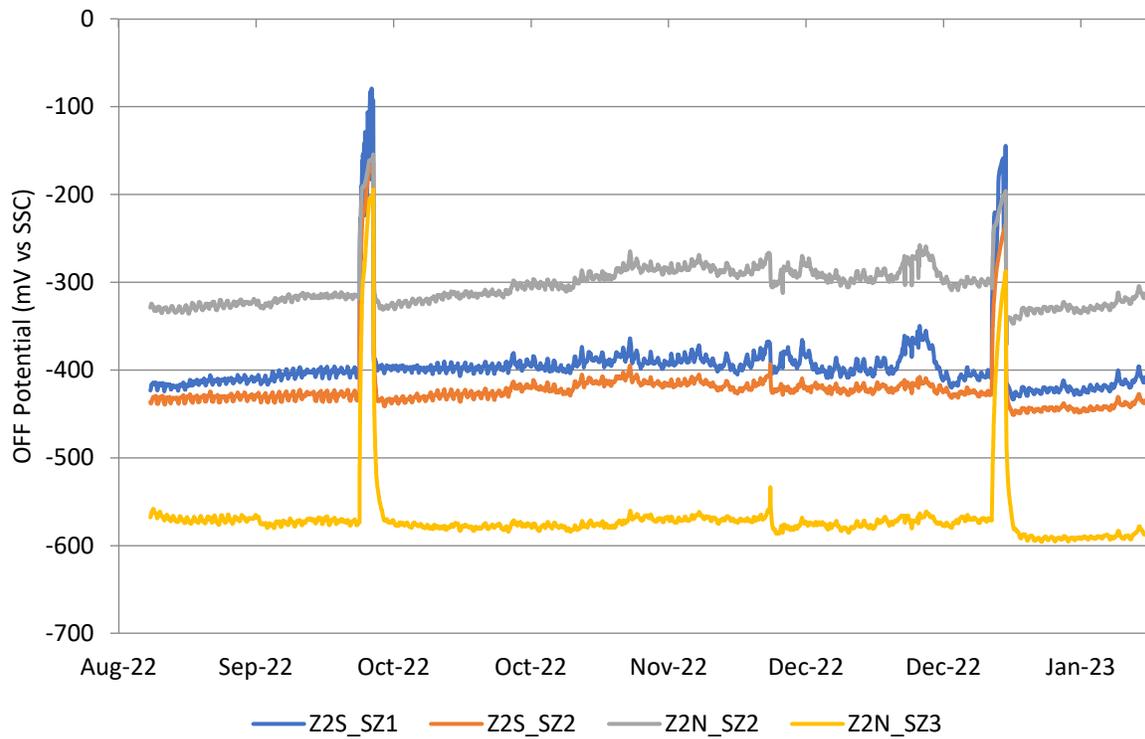
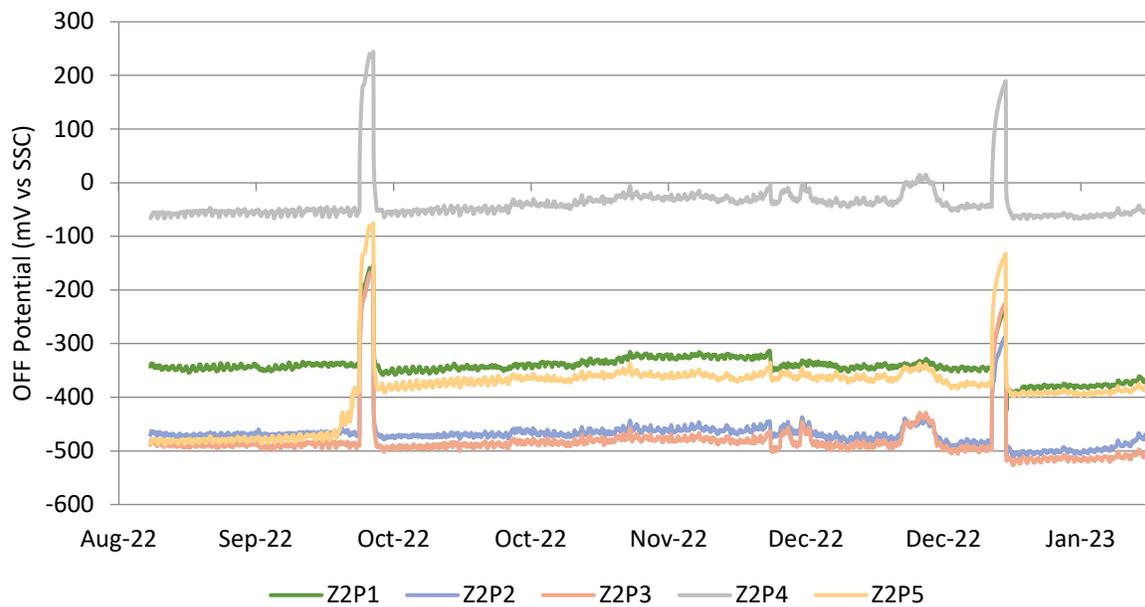


Figure 19. OFF Potential Measurements for Zone 2 of the ICCP System



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## References

<sup>1</sup>ACI PRC-222-19 "Corrosion of Metals in Concrete." American Concrete Institute. (2019)

<sup>2</sup>ASTM C876/C1152M-15 "Standard Test Method for Corrosion Potentials of Uncoated Reinforcing Steel in Concrete." ASTM International. (2015)

<sup>3</sup>ASTM C1152/C1152M-20 "Standard Test Method for Acid-Soluble Chloride in Mortar and Concrete." ASTM International. (2020)