Corrosion protection challenges for Australia's longest single-lane bridge in a harsh marine environment

Atef Cheaitani [1], *Bob* Brown, and *Rhett* Lamperd

[1]Remedial Technology Pty Ltd, Sydney, Australia

Abstract. The Mission River Bridge in Weipa, Queensland, is Australia's longest single-lane bridge spanning 1040 meters. Built in 1971 with a 35-year design life, the bridge plays a key role in supporting the region's mining operations and its local communities. Over time, its steel piles have suffered significant section loss due to Microbially Induced Corrosion (MIC) in the aggressive marine environment. To mitigate further degradation and extend the bridge's service life, Impressed Current Cathodic Protection (ICCP) systems were installed. The composite piles, consisting of prestressed concrete in the upper section and steel in the lower section, are protected by the ICCP systems up to mid-tide level. A Mixed Metal Oxide (MMO) ribbon anode system was also installed to protect the atmospheric zones, including the piles and sections of the headstocks. This paper presents a case study on the cathodic protection systems implemented for this complex marine structure. It highlights the technical challenges posed by MIC and the harsh environmental conditions, and it critically examines the limitations of current cathodic protection standards in addressing protection criteria for similarly complex structures.

1 Introduction

The Mission River Bridge (MRB), located in Weipa in Far North Queensland, functions as a vital transport artery supporting the region's bauxite mining operations and serving local communities. Located in an aggressive tropical marine environment, the bridge faces significant challenges regarding the long-term durability and structural integrity of its components due to severe environmental conditions.

This paper examines the corrosion protection strategies applied to the Mission River Bridge, focusing on the operational challenges in monitoring and maintaining its ICCP systems. It underscores the vital role of cathodic protection in extending the bridge's serviceability far beyond its original design life.

The original bridge construction in 1971 did not include provisions for a cathodic protection (CP) system. In 1993-94, a Mixed Metal Oxide (MMO) water anode impressed current cathodic protection (ICCP) system was installed to protect the portions of the piles below mid-tide level. At the same time, concrete repairs were carried out on some of the walers, and an embedded discrete anode CP system was installed within the walers, stems and headstocks.

The original water anode system, installed in 1993-94, remains operational and has undergone significant upgrades, including replacement of the anodes, reference electrodes and an upgrade of the control system. After more than 25 years of operation of the ICCP concrete system, the original embedded discrete anode system for the walers, stems and headstocks was decommissioned. Around 2018, two new ICCP systems were introduced and commissioned. These included a ribbon anode system installed on the piles above the high-tide level and a new internal anode system designed for cathodic prevention. The latter was gradually implemented over several years for various builddowns on sections of the headstocks to enhance structural integrity, with the system being fully commissioned in 2018.

This paper provides a detailed overview of the currently operating Impressed Current Cathodic Protection (ICCP) systems implemented on the bridge. It also discusses the protection criteria applied for the monitoring and adjustment of the ICCP systems, along with the complexities involved in applying some of these criteria to various elements of the bridge.

2 Description of the structure

MRB includes 57 piers that support a railway bridge superstructure and a single-lane road bridge deck. Each pier was constructed using 6-20 piles driven into the riverbed.

The piles are a combination of composite piles, including a precast prestressed concrete segment and steel segment, and steel piles which were initially used as test piles to confirm driving depth conditions but were incorporated into the permanent works.

There are 3 main pile types:

- Steel HP2 pile (test piles). The HP2 pile is an octagonal steel section approximately equivalent to a 400 mm diameter tube with 16 mm wall thickness. The steel piles were initially used as the test piles during construction to confirm the driving depth but were later incorporated into permanent works.

1 Corresponding author: atef.cheaitani@remedialtechnology.com.au

- Composite Type 1 piles. These have a composite design with an octagonal prestressed concrete upper segment and a lower segment of Universal Bearing Pile (UBP) steel pile section.
- Composite Type 2 piles. These have a composite design with an octagonal prestressed concrete upper segment and a lower segment of octagonal steel pile section.

The steel segments of the composite piles are buried in the riverbed / riverbank, except between Pier 5 and Pier 28 inclusive. At these piers, a portion of the steel segment protrudes above the riverbed and is immersed in river water. This steel segment is referred to as a 'pile tip'.

The exposed pile tips have suffered from Microbially Induced Corrosion (MIC) over their history and significant section loss has occurred.

As a means of strengthening the corroded piles, 178 coated steel pile splints were installed between 1998 and 2011. The splints comprised a cylindrical steel shell split into vertical halves with flanges welded to the joints, bolted together underwater, and then filled with grout. 27 of the splints were filled with cementitious grout, and 151 splints were filled with epoxy grout. The splints concealed many of the exposed pile tips, however many pile tips remain exposed.

3 Description of the current operating cathodic protection systems

3.1 Water Anode (WA) ICCP System

<u>The WA system is designed to protect the following:</u>

- The buried and permanently immersed sections of the steel piles (Section 4, shown in Figure 1 below).
- Test piles and retrofitted steel pile splints.
- The concrete section up to the mid-tide level (Section 3, shown in Figure 1 below).

The system utilises Mixed Metal Oxide (MMO) anodes located on the riverbed. For monitoring purposes, 97 zinc reference electrodes are installed, classified into high and low references. The high reference electrodes measure the potential of reinforcing bars and prestressing strands in Prestressed Concrete (PSC) piles below mid-tide level. The low reference electrodes monitor the steel potential at the pile tips.

3.2 Pile Anode (PA) ICCP system

The Pile Anode ICCP system is designed to protect the reinforcing bars and prestressing strands of the Prestressed Concrete (PSC) piles, both above the high-tide level and below the headstock builddown soffit level in selected rail and road bridge piles (shown in Figure 1).

This system incorporates MMO ribbon anode installed in 7-10 mm wide x 30 mm deep slots (perpendicular to the concrete surface) in selected piles. Monitoring is conducted using 56 Silver/Silver Chloride reference electrodes which measure the potential of reinforcing bars and prestressing strands within the piles.

3.3 Internal Anode (IA) ICCP system

<u>The Internal Anode (IA) system is designed to protect:</u>

- The reinforcement of certain existing headstocks.
- Sections of selected piles within each headstock builddown (an extension below the original soffit level completed to strengthen some headstocks).
- Localised areas with headstock patch repairs.

For the Internal Anode system, ribbon anode was utilised. In the builddown sections, the ribbon anode was installed using spacers attached to the reinforcing bars during construction. For localised repair areas on the headstocks, the ribbon anode was installed in slot cuts into the concrete.

In the builddown sections, the ICCP system was primarily designed for cathodic prevention, with the goal of eliminating any risk of corrosion initiation in the newly constructed concrete elements to enhance structural integrity.

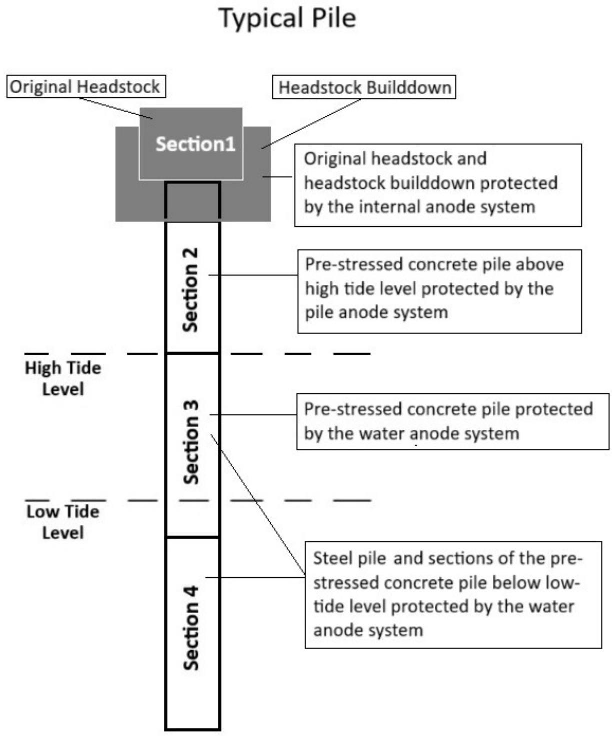

Fig. 1. IA, PA and WA ICCP systems

4 Description of the control system

The bridge's control system is a distributed, non-proprietary system integrated with the Principal SCADA system for monitoring purposes. Power supply units and communication equipment is located on 12 accessible platforms along the length of the bridge.

The Water Anode (WA) system is fully remote-controlled, allowing for centralised management and operation. In contrast, the Pile Anode (PA) and Internal Anode (IA) systems are equipped for remote functional checks, however, detailed system testing and adjustments are carried out locally from the 12 platforms.

Additionally, the control system includes a global cathodic protection current interruption capability, an essential feature to ensure accurate system testing in accordance with the relevant cathodic protection standards.

5 Cathodic protection criteria

The cathodic protection criteria for the system are in accordance with the applicable Australian Standards for concrete and steel structures [AS 2832.5 – 2008 (R2018) and AS 2832.3 – 2005 (R2016)].

<u>The protection criteria to AS 2832.5 – 2008 (R2018) are as follows:</u>

No instantaneous OFF steel/concrete potential shall be more negative than −1100 mV for plain reinforcing steel or more negative than −900 mV for prestressing steel with respect to Ag/AgCl/0.5M KCl.

The system adjustment shall be based on meeting one of the following criteria:

a) *A potential decay criterion over a maximum of 24 h of at least 100 mV from Instant OFF.*
b) *Extended potential decay criterion over a maximum of 72 h of at least 100 mV from the Instant OFF potential subject to a continuing decay and the use of reference electrodes (not potential decay sensors) for the measurement extended beyond 24 h.*
c) *Absolute potential criterion. An Instant OFF potential more negative than –720 mV with respect to Ag/AgCl/0.5M KCl.*
d) *Absolute passive criterion. A fully depolarised potential, or a potential which is continuing to depolarise over a maximum of 72 h after the cathodic protection system has been switched OFF, which is consistently less negative than -150 mV with respect to Ag/AgCl/0.5M KCl.*

The protection criterion for the steel piles is in accordance to AS 2832.3 – 2005 (2016). *The system shall maintain a potential equal to, or more negative than, -800 mV with respect to a Silver/Silver Chloride seawater reference electrode. To ensure that overprotection does not cause accelerated disbondment of the coating, or other deleterious effects, a potential corrected for voltage gradient error should be measured. For coated structures, the polarised potential should not be more negative than -1.2 V with respect to a Copper/Copper Sulfate reference electrode. Less negative values may be appropriate for coatings that are more susceptible to cathodic disbonding. Where sulfate-reducing bacteria are active, a more negative potential may be required for protection.*

6 Applicability of CP criteria for PA and IA system

For the reference electrodes embedded in concrete (PA and IA systems), the stability of these electrodes is influenced by changes in concrete chemistry over time, which can affect the precision of absolute potential measurements. Despite potential variations, the depolarisation test is performed to confirm protection levels as long as the reference electrode remains stable during the depolarisation period.

Compliance with criterion a) and criterion b) of AS 2832.5 – 2008 is not affected by the calibration of embedded reference electrodes. For criterion a), either true or pseudo (inert) reference electrodes can be used, while criterion b) requires the use of true reference electrodes as specified in the standard. In the case of this system, true reference electrodes are used for both the PA and IA systems.

For the reference electrodes embedded in concrete exposed to atmospheric conditions, the application of criterion c) and criterion d) is limited, as post-installation calibration of these electrodes is not feasible especially for the IA system. Calibration after installation is performed using a portable external reference electrode positioned on the concrete surface. AS 2832.5 – 2008 addresses the challenges of reference electrode calibration, and routine calibration is performed if depolarisation criteria are not employed.

<u>In summary, the application of AS 2832.5 criteria for system adjustments in concrete-based PA and IA systems is as follows:</u>

- Criterion a) and/or criterion b) are applied for both the PA and IA systems.
- Criterion c) and criterion d) are applied only when external calibration of reference electrodes is performed.

7 Applicability of CP criteria for WA system

For the Water Anode (WA) system, regular calibration of zinc reference electrodes is performed using a portable seawater reference electrode (Ag/AgCl/0.5M KCl). This calibration is performed from the 12 platforms located along the bridge. The resulting calibration offset is then incorporated into the control system to adjust the potential readings and obtain a calibrated potential for all reference electrodes to an Ag/AgCl 0.5MKCl reference electrode.

For the steel piles, potentials are maintained at or more negative than -800 mV with respect to the Ag/AgCl/0.5M KCl reference electrode. No instant OFF potential exceeds -1.2 V versus the Copper/Copper

Sulphate reference electrode, which corresponds to -1133 mV when calibrated against Ag/AgCl/0.5M KCl.

For the immersed sections of the prestressed concrete piles, instant OFF potentials are maintained at or more negative than -720 mV relative to Ag/AgCl/0.5M KCl, with an upper limit of -900 mV for instant OFF potentials with respect to Ag/AgCl/0.5M KCl to prevent hydrogen embrittlement.

8 Test data

8.1 Internal Anode (IA) system

For the internal anode system, Silver/Silver Chloride reference electrodes were installed within the protected elements to facilitate monitoring. The protection criteria outlined in AS 2832.5 were applied for adjusting the ICCP current to achieve the desired level of protection. Since the reference electrodes cannot be calibrated within the concrete, the "24-hour decay criterion" (protection criterion a) from the applicable standard was used to assess system performance and current adjustment.

For the majority of reference electrodes, the 100 mV decay criterion was successfully met. However, in some zones, due to circuit under-design or to high concrete resistivity, there were limitations in current adjustment as the circuit voltage reached 9 V (AS 2832.5 indicated voltage levels applied to bare titanium conductors should be limited to 9 V d.c. in chloride contaminated concrete). Overall, the system is performing satisfactorily. The data from Group 4 circuit is provided below:

Table 1. Data from IA system – Group 4

Reference	Instant OFF (mV)	24h OFF (mV)	24h Decay (mV)
1	-460	-204	256
2	-399	-143	256
3	-446	-190	256
4	-483	-266	217
5	-460	-182	278
6	-510	-115	395
7	-138	409	547
8	-515	-203	312
9	-534	-207	327
10	-528	-188	340
11	-540	-444	96
12	-660	-544	116
13	-463	-319	144

8.2 Pile Anode (PA) system

For the Pile Anode (PA) system, the primary challenge is to prevent overprotection of the prestressed strands from the ICCP system. Overprotection is assessed using protection criterion c) from the applicable standard, which requires that the Instant Off (IO) potential should not exceed -900 mV. Since the potential of reference electrodes embedded in concrete may drift over time, external calibration was incorporated into the system's monitoring process to detect any areas of overprotection and make necessary adjustments.

The external calibration process involves performing potential mapping on the concrete surfaces while interrupting the cathodic protection current to accurately assess the system's performance. Typical data from Group 4 circuit is provided below. The true potential (Instant Off) of the prestressed strands, as shown in Table 2 below, falls within the expected range for an atmospheric ICCP system. External calibration revealed potentials greater than -900 mV relative to Ag/AgCl/0.5M/KCl in certain locations of the piles within the splash zone. To address this, current adjustment was made to the relevant circuits to eliminate overprotection in these areas of the piles.

Table 2. Data from PA system taken using external reference electrode – Group 4

Reference	Instant OFF (mV)	24h OFF (mV)	24h Decay (mV)
1	-650	-341	309
2	-21	116	137
3	-476	-306	170
4	-463	-252	211
5	-369	-127	242

8.3 Water Anode (WA) system

For the Water Anode (WA) system, the test data presented below reflects the Instant Off calibrated potential to a seawater reference electrode (Ag/AgCl 0.5M KCl) for prestressed strands (concrete) and steel piles (steel) prior to system adjustment.

The displayed data indicates the potentials for both the prestressed strands (concrete) and steel piles (steel) at low and high tides. The protection criteria for the concrete references are to maintain potentials between -720 mV and -900 mV to Ag/AgCl 0.5M KCl reference electrode. For the steel reference electrodes, the protection criteria are to maintain potentials between -800 mV and -1133 mV for the same reference electrode.

At the time of data retrieval, all steel reference electrodes met the protection criteria, and maintaining the system at this potential level was deemed necessary to control the problem of microbial-induced corrosion (MIC). However, for the concrete reference electrodes, there is a risk of overprotection at both low and high tides, as the potential is more negative than -900 mV.

Based on this data, the current was lowered for these circuits to maintain the protection criteria as outlined in the applicable standards. While reducing the current may mitigate the risk of overprotection in the prestressed sections of the composite piles, it could increase the corrosion risk for the steel sections due to MIC.

This current adjustment which balances between under protection and overprotection of the composite piles represents one of the key challenges of monitoring the WA system, as current standards do not address situations like this case, posing significant challenges for asset owners on how to optimise the system's operation while minimising associated risks.

Table 3. Data from WA system – Groups 9 and 10

Reference	Location	IO - High tide (mV)	IO - Low tide (mV)
Group 9	steel	-985	-1030
Group 9	concrete	-956	-1123
Group 9	concrete	-992	-1107
Group 9	concrete	-984	-1019
Group 9	concrete	-986	-1049
Group 10	concrete	-998	-1086
Group 10	concrete	-957	-1018
Group 10	steel	-1002	-1031
Group 10	concrete	-993	-1088
Group 10	concrete	-1009	-1101
Group 10	steel	-1002	-967
Group 10	concrete	-993	-1054

9 Challenges associated with system monitoring

For the IA system, the monitoring process can be performed based on the applicable standards. The 24-hour decay criterion is normally used, and system adjustments are made according to the relevant standard guidelines. The performance of the testing at low tide has been adopted as it allows for the elimination of the impact of tidal level variation on the potential of embedded rebar during the 24-hour decay period.

For the PA system installed for the atmospheric sections of the piles above the high tide, although the embedded reference electrodes are true references (not pseudo-reference electrodes) and were strategically placed in high and low corrosion risk areas, the absolute potential criterion cannot be relied on to confirm that there is no overprotection. This is because these references cannot be calibrated after installation. To resolve this critical issue, external targeted potential verification is incorporated into the monitoring process to identify potential sites of overprotection that may not be identified from the embedded reference electrodes alone. Although this process is time-consuming and requires boat access to perform testing on the external surfaces of the piles, it was assessed during the monitoring of the pile anode system that overprotection is not desirable, and this additional external calibration is essential as deviations up to 50 mV were observed.

For the water anode system, there are multiple serious challenges associated with monitoring. There are large tidal changes for the bridge, and it was noted that there is a substantial difference in potentials between high and low tides. Measuring the potential at both high and low tides was incorporated into the monitoring process.

The most critical challenge for monitoring the water anode system is the significant variation in the applicable potential limits (as specified by the standards), between the prestressed sections of the piles and the steel piles.

At the bridge site, Microbial-Induced Corrosion (MIC) driven by sulfate-reducing bacteria (SRB) or other microorganisms occurs in anaerobic conditions. The application of high negative potentials disrupts microbial activity by inhibiting oxygen and nutrient access, promoting hydrogen evolution at the metal surface to suppress SRB metabolism, and increasing local alkalinity, further restricting microbial growth. The presence of SRB at this site has been confirmed, and historical ICCP system data shows that elevated negative potentials have been employed to mitigate MIC.

The high negative potentials required for the steel piles introduces the risk of hydrogen embrittlement for the prestressed sections of the piles. Hydrogen embrittlement occurs when hydrogen atoms generated by cathodic protection diffuse into the embedded steel, leading to embrittlement, especially in high-strength materials such as prestressed steel. To date, there is no visual evidence of hydrogen embrittlement in the prestressed concrete piles, possibly due to factors such as relatively low-stress levels in the prestressing strands and the good quality of the concrete. Visual evidence is obtained through routine inspections for cracks and surface defects on the concrete piles above water, while divers conduct equivalent inspections on the submerged section of the concrete piles. The major challenge for the ongoing monitoring of the water anode system is to set the cathodic protection current to achieve corrosion protection at high and low tides, maximise the chance of combating MIC corrosion for the steel piles, and eliminate or reduce the risk of hydrogen embrittlement on the prestressed concrete piles.

10 Conclusions

The management and monitoring of cathodic protection systems for composite piles involves distinct challenges, primarily due to the variation of potentials at high and low tides and the interplay between corrosion mechanisms, Microbial-Induced Corrosion (MIC), and the risk of hydrogen embrittlement [3-8].

Current industry practices, guided by the applicable Australian Standards, have established potential limits to mitigate these challenges. However, the complexity introduced by factors such as sulfate-reducing bacteria (SRB) necessitates maintaining high negative potentials to control MIC, which, in turn, increases the risk of hydrogen embrittlement in the prestressed concrete piles.

The key issue is the significant knowledge gap in cathodic protection for composite piles, which complicates system management. Current approaches rely heavily on site-specific conditions rather than a standardised framework. This limitation hinders the industry's ability to balance corrosion control with the avoidance of overprotection and hydrogen embrittlement.

In conclusion, while cathodic protection has proven effective in mitigating MIC and managing corrosion risks, the absence of robust research leaves the industry with uncertainties in managing overprotection and hydrogen embrittlement risks. Until comprehensive studies provide clearer guidance, the approach adopted for this is based on leveraging site-specific monitoring and regular inspections to optimise long-term performance. This highlights the urgent need for further research and development to refine cathodic protection strategies for composite piles.

The subject bridge was originally constructed in 1971 with a design life of 35 years, set to last until 2006. However, its service life has now been extended at least until 2042, made possible through the implementation of ICCP systems on various high-risk elements of the structure. This case study highlights the critical role of cathodic protection in significantly extending the service life of infrastructure.

The successful extension of the bridge's design life is not solely attributed to the ICCP technology itself, but also to the rigorous and well-structured maintenance program that accompanies it. This program includes regular diving inspections for detailed inspection of the condition of the piles, timely replacement of faulty ICCP components, and ongoing monitoring and maintenance of the systems installed on the bridge. Without these sustained efforts, even the most advanced ICCP system would not have achieved the same level of performance.

This case underscores the broader importance of cathodic protection, coupled with effective maintenance strategies, in preserving and extending the lifespan of critical infrastructure, reducing the need for costly replacements and ensuring long-term structural integrity.

11 References

1. Standards Australia, AS 2832.5 – 2008 (R2018), Cathodic Protection of Metals, Part 5: Steel in Concrete Structures.
2. Standards Australia, AS 2832.3 – 2005 Cathodic Protection of Metals, Fixed Immersed Structures.
3. The Influence of Cathodic Protection on Hydrogen Embrittlement of Prestressed Concrete Structures. Paul Lambert et al., Materials and Corrosion.
4. Hydrogen Embrittlement of Prestressed Steel Wires in Cathodically Protected Structures. M. J. Robinson et al., Corrosion Science.
5. Effect of Impressed Current Cathodic Protection on Hydrogen Embrittlement of Prestressed Steel. W.J. Buttler and J.P. Broomfield, ACI Materials Journal
6. Cathodic Protection and Hydrogen Embrittlement of High-Strength Prestressed Steel. D. A. Koleva, Construction and Building Materials.
7. Impact of Cathodic Protection Current on Hydrogen Production and Embrittlement in Prestressed Concrete Structures. T. V. Nguyen et al., Journal of Structural Integrity and Maintenance
8. Long-Term Effects of Cathodic Protection on Prestressed Concrete Bridge Components. US Department of Transportation, Federal Highway Administration. Publication No. FHWA-RD-96-029. November 1996.