Hybrid Anode Treatment for the Management of Corrosion to Reinforced Concrete Bridge Piles in an Estuarine River

Dr. Liam Holloway, Principal Engineer, MEnD Consulting Pty Ltd

ABSTRACT

Like most of Australia, WA has hundreds of reinforced concrete bridges in regional areas that are exposed to relatively aggressive conditions. It is well known that chloride induced corrosion of the reinforcement presents a risk to the structural integrity of bridges. This is especially the case for bridge piers, which can be exposed to saline waters with tidal or seasonal variations; accelerating chloride ingress and in turn the rate of deterioration. This paper presents a recent case study where a hybrid anode system was installed to manage the risk of corrosion to the cylindrical reinforced concrete columns on two adjacent bridges. The bridges cross the estuarine Serpentine river South of Perth, Western Australia and were of similar construction. One of the bridges was constructed in the early 1980s while the duplication was constructed in the early 1990s. The paper will discuss the basic principles of Cathodic Protection (CP) for reinforced concrete; and how hybrid anodes systems offer a method to manage the risk corrosion for remote regional structures, where impressed current cathodic protection systems may be less practicable. The paper will also share some of the practical implications with installing hybrid anode systems learnt from the project.

1 INTRODUCTION

The risk of corrosion to reinforced concrete is one of the key parameters that determines the durability and in turn service life of bridges. In rural Australia there are literally hundreds of small reinforced concrete bridges that are exposed to relatively aggressive environments that can result in premature degradation. The two primary causes for reinforced concrete corrosion are carbonation and chloride contamination of the cover concrete. Carbonation of the cover concrete will occur in most environments and is often an issue in situations where there is very low concrete cover, or older structures where the concrete may have been of a lesser quality. In Australia, chloride induced corrosion is typically only an issue for bridges in marine environments, or locations where there are high chloride contents in the local soil or ground water. For the purposes of this paper our discussions will focus on the risk and management of chloride induced corrosion.

Bridge owners have a wide range of options to manage the risk of chloride induced corrosion. At the time of design and construction adequate concrete quality, cover, and even the use of protective coatings can all be implemented to ensure an adequate design life. In very harsh environments or structures with a design life of more than 100years even the use of alternative materials, such as stainless-steel reinforcement can be considered. For existing bridges, especially those nearing the end of their design life, retrospective strategies can be used to help achieve or extend their service life. The selection of the most suitable methods to implement will depend on the extent and nature of deterioration, budget, required extension of service life, duty of the bridge, and location to name a few. Common strategies for reinforced concrete bridge elements will include, conventional concrete patch repairs, penetrating sealers or waterproofing agents, film forming coatings, impressed current cathodic protection (ICCP) and galvanic anode treatments.

Penetrative sealers such as silane treatments and coating systems are a relatively simple method to use. In cases where airborne chloride contamination is a risk, and the existing contamination levels are relatively low they can be very effective in reducing the risk of chloride induced corrosion. These systems can also be included as part of a multi-faceted strategy incorporating other techniques including ICCP or galvanic anodes. However, silanes and coatings are not as effective when chloride levels within the concrete have already reached significant concentration at the reinforcement or where long-term maintenance of the coating system is impractical.

One of the most well proven and effective methods to manage the risk of corrosion in reinforced concrete structures with high levels of chlorides present at the depth of the reinforcement, is ICCP. Direct experience with ICCP of concrete structures in Australia dates back to the 1980s (Grapiglia and

Green, 1995) and abroad to the 1970s for above ground reinforced concrete structures and the 1960s for below ground reinforced concrete structures (Wyatt, 1994). When designed, installed and maintained correctly ICCP systems can provide very reliable and confident long-term protection against reinforcement corrosion, with the ability to achieve a design life of greater than 50 years. However, one of the critical problems with ICCP systems is the need to monitor and adjust the system periodically. Another issue is the need for a constant power supply. These can both become problems for bridges in remote or regional areas where experienced CP technicians may not be readily available or there is no reliable access to power. While, remote-controlled and solar powered systems can alleviate some of these concerns, such facilities can add significant cost in terms of the initial capital expenditure and the ongoing maintenance. There is also the “out of sight, out of mind” factor that can lead to an ICCP system becoming neglected. When an ICCP system is not operated correctly, or there are design and installation faults, it can result in its ineffective operation, failures or even damage to the structure.

Over the past 10 years there has been a growing number of cases where hybrid anode systems have been implemented for bridge structures including several examples in the United Kingdom, New Zealand and Australia. Hybrid anode systems may not be capable of providing long term Cathodic Protection (Green, 2017). However, hybrid anode systems can deliver a short-term level of polarisation that is sufficient to improve the condition of the reinforcing steel’s passive layer with the combined benefits of long-term galvanic corrosion control. The attractiveness of hybrid anode systems for the treatment of reinforced concrete structures in remote or regional locations is that no power is required for the long-term operation, they are relatively maintenance free, and they do not require ongoing monitoring or adjustment to be functional.

2 THE MECHANISMS OF CATHODIC PROTECTION IN REINFORCED CONCRETE

To understand the way hybrid anodes can act to manage the risk of reinforcement corrosion in concrete; it is beneficial to first consider the mechanisms of CP in reinforced concrete. While the ability for ICCP systems to effectively mitigate reinforcement corrosion is well accepted, the scientific reasons why this occurs are not clear-cut or attributed to a single mechanism. For example, the interpretation that cathodic polarisation renders the metal immune to corrosion by placing it in the ‘Fe’ or ‘Immune’ portion of the Pourbaix diagram is not the key mechanistic step. To reach such an immune state, the steel would need to be polarised to an extent where the dominant cathodic reaction is water reduction. This increases the threat of hydrogen uptake into the steel and in turn hydrogen embrittlement, which must be avoided. The mechanism of CP is considered likely to be a combination of the ability for the negatively polarised steel to:

1. Generate hydroxyl ions which re-establish an alkaline pH at the steel surface, which promotes the passive layer protecting the steel,
2. Repel negatively charged ions (such as Cl-) some distance away from the steel surface reducing the risk of passive layer breakdown, and
3. Make it kinetically difficult for dissolution (anodic) reactions to occur on a catholically polarised metal surface.

These three mechanisms are a convenient way of thinking about CP, since they make it possible to realise that the absolute value of cathodic current density is not important if (and only if) there is sufficient current to ensure protection is maintained. The notion of small currents causing effective CP was also mentioned by Glass and Hassanein (2003). Furthermore, these three mechanisms also support the notion that their effect may persist even some time after ICCP has been removed (Christodoulou et al, 2010), on the basis that local restoration of the environment at the surface of the reinforcing steel is beneficial.

3 HYBRID ANODE TREATMENTS FOR REINFORCED CONCRETE

The concept of hybrid anode systems is to embed an array of zinc (Zn) anodes into the concrete, that are interconnected via a titanium wire. The hybrid system is initially operated in an impressed current mode, before being disconnected from the power source and maintained as a sacrificial anode system. The UK patent holders for the technology have published a paper describing the system and its principles for providing protection (Glass et al, 2008). In the paper, it is proposed that during the initial impressed current phase acts to rapidly re-passivate the steel by increasing the local alkalinity and reduced the concentration of chloride ions at the steel surface. The subsequent galvanic phase aims to maintain this passivity by providing a lower current flow from the anodes to the steel due to the galvanic potential difference between the two metals.

During the impressed current phase, the anodes are typically polarised to a set voltage, of 9-12V depending on the design and the environment. However, in the case of some proprietary systems and structures with pre-stressed or post-tensions steel the voltage can be lower. The target during the impressed current phase is to deliver a nominal amount of charge to the steel, i.e. 50kC/m^2 of steel surface area. The time taken to deliver this is a function of the total circuit resistance and in particular the resistance of the concrete and the grout encasing the anode. It is generally anticipated that the required charge can be passed in 7-28 days. During the galvanic phase the amount of current delivered is also governed by the resistivity of the circuit and the potential difference between the steel and the anodes. While, there is limited data published on the anticipated current densities delivered by hybrid anodes during the galvanic phase, in the authors practical experience it ranges from <0.1mA/m^2 to 2mA/m^2.

In terms of the design life of a hybrid anode it is dependent on several factors. Firstly, the anodes have a theoretical amount of charge that they can deliver. This is based on the mass of Zn in the anode and determined using the Faraday equation, in a similar fashion that it may be done for galvanic anodes used to protect steel piles in seawater. During the impressed current phase, the amount of metal loss can be calculated directly based on the amount of charge passed. During the galvanic phase the amount of current can be measured periodically to determine the typical charge passed. This will tend to vary depending on the resistivity of the concrete on a given day. To this end, you may expect to see lower currents during summer when a concrete element is very dry compared with those in winter during raining periods. Once the typical amount of current delivered by the anodes is established, the life of the anodes can be predicted by extrapolating the charged passed until the zinc has been fully depleted. Based on this process it is typical to predict a design life in the order of 30-50years for hybrid anode systems.

4 THE SERPENTINE RIVER BRIDGES CASE STUDY

4.1 Level 3 Condition Assessment outcomes

A hybrid anode system was designed, installed and commissioned for the management of the risk for reinforcement corrosion initiation to the pier columns of two bridges that span the serpentine river Approximately 100 km south of Perth. The two bridges are identical in design with the first bridge being constructed in 1981 and the second in 1992 (Figure 1). Located 5km from the coast and 2.7km from a salt water inlet the water in the river at the location of the bridges is brackish and has a small tidal variation.

Figure 1 View of Bridge from river bank

Each bridge carries a dual lane, single carriageway. The bridges comprise of pre-stressed reinforced concrete I beams supporting a cast in-situ slab. The superstructure is supported over four reinforced concrete piers and two abutments. Each pier has a post tensioned headstock, and three circular reinforced concrete columns.

In 2012 AECOM conducted level 3 inspections for each bridge, which included chloride content testing and diffusion modeling for the reinforced concrete elements. Elevated chloride levels were found during testing in 2012 within the pier columns in both bridges. At the average depth of the reinforcement (~40mm) the chloride levels were greater than 0.1 wt.% concrete, which represented a moderate to high risk for corrosion initiation according to the broadly accepted risk criteria (Broomfield, 2007). While, there was some evidence of corrosion initiation at the location of breakouts, there was not widespread concrete cracking, delamination or spalling identified.

Since the levels of chloride contamination had already reached a critical concentration, it was considered that coatings or penetrative silane treatments would only provide limited benefit to the structure. CP was proposed using a galvanic anode system installed within fiber reinforced plastic jackets. It is assumed that the option for an ICCP system was discounted based on the regional location of the bridge, the lack of a nearby permanent power supply, and the high potential risk for vandalism given that the areas under the bridge are regularly frequented by the public. Ultimately, a Hybrid anode system was specified in 2016 and installed in 2017 by Fulton Hogan, with technical support from MEnD Consulting.

4.2 Hybrid Anode System Design

The hybrid anode system was designed with a 30-year design life, based on an assumed long term current density of $2mA/m^2$. The system was broken up into four separate zones for each bridge with each pier as one zone. There was a total of 18 Hybrid anodes per zone, or 6 per pier column. The anodes were a Duoguard 1000® Hybrid Anode, 220 mm long, 18 mm diameter. The design also incorporated one permanent Ag/AgCl reference electrode per column to allow for ongoing monitoring. Figure 2 shows a typical elevation of the pier with the anode arrangement and ancillary items. The anodes were installed centrally in the pier at approximately 225mm centers. The anodes were installed in predrilled holes on a 15 degree angle.

During the impressed current phase a total of $50kC/m^2$ of steel surface areas was to be passed prior to connecting the anodes directly to the steel reinforcement for the galvanic phase. To power the system it was nominated to use battery power due to the site constraints and the inability to secure it overnight.

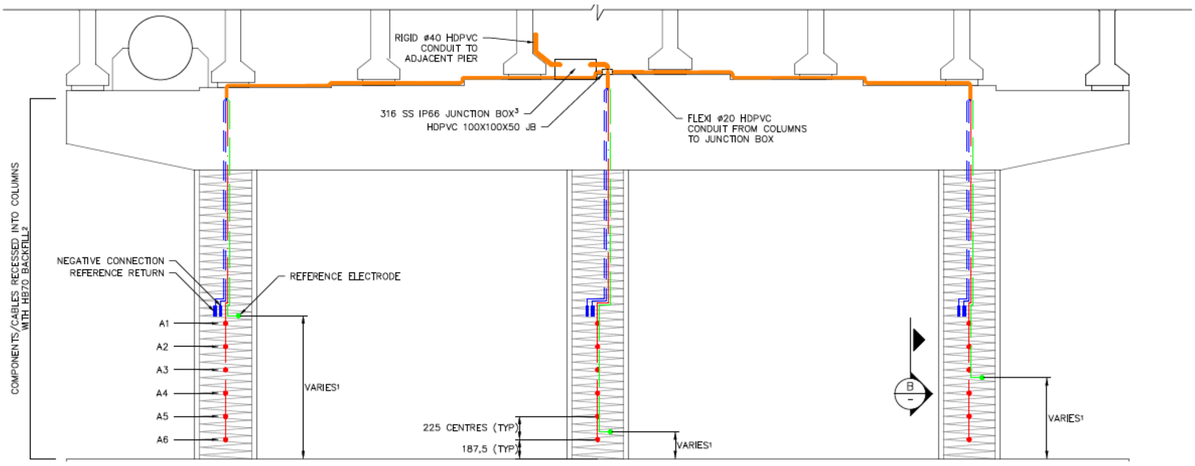

Figure 2 Typical pier elevation.

4.3 Construction and Commissioning

Figure 3 Installation of cable chase and core holes for Hybrid Anode (left); Hybrid anode array prior to installation (right)

The hybrid anode system was installed as part of an overall bridge maintenance contract being undertaken by Fulton Hogan during April 2017. Because the site needed to be fully secured overnight to minimize the risk of vandalism by the public the construction sequence was such that all of the anodes had to be fully installed, grouted into place and routed back to the central junction boxes prior to energisation taking place. This meant that some of the anodes were installed for 2-5 days before they could be energised.

The time between installing the anodes and energizing them made a significant difference in the time required to pass the 50kC/m^2 of charge required for the impressed current phase of the commissioning. In cases where the anodes could be installed and then energised within 24 hours or less, the total time to pass the required charge was typically 17 days. When the time between installation and energization was 2 days or more, the time required to pass the charge was approximately 50 days. This large difference in the time required to pass the charge was attributed to the change in resistivity of the grout used to encapsulate the anodes as it set. The proprietary grout is designed to maintain the anodes in an active state during the galvanic phase, but it is also designed to provide a very low resistivity electrolyte for the impressed current phase before it hardens. After the grout has hardened the circuit resistance increase and in turn the current passed at the set driving voltage can be significantly less.

After the completion of the impressed current phase the system was changed over to the galvanic phase by directly bonding the anodes circuit to the reinforcing steel. After approximately 1 week the system was then tested to assess the performance. Because there aren't specific performance criteria for hybrid anode systems it was benchmarked against the criteria set out in AS 2832.5-2008, which is relevant to ICCP for reinforced concrete.

The galvanic current density for each column at the time of testing ranged from 0.28mA/m^2 up to 8.95 mA/m^2. However, the majority of the columns were delivering a galvanic current density of 0.78 to 1.56 mA/m^2. 10 of the 24 columns passed the 24 hour 100mV potential decay criteria, and 3 others were considered to be a near pass, as they achieved a decay of >80mV.

In addition to the Australian Standard, ISO 12696:2012 provides guidance on the monitoring the performance of galvanic anodes and hybrid systems where they may not meet the criteria above and it is not possible to increase the current to the steel. The standard allows for assessment of performance by determining the corrosion risk. One of the methods proposed for measuring the corrosion risk is to perform corrosion rate measurements. A corrosion rate of 2mA/m2 indicates passive steel. Over time a falling trend in corrosion rate and a trend towards more positive reinforcement potentials indicates protection is being achieved. At the time of the testing the corrosion rate in all cases, apart one, was less than 2mA/m^2. The one case where the corrosion rate was above 2, it was only measured to be 2.9mA/m^2.

The long term monitoring of the structure commenced in February 2019. The current densities being delivered ranged from less than 0.01 to 0.24 mA/m^2. The 24-hour decay potentials were also very low ranging from effectively 0 to 21mV. These low levels of polarisation made it impractical to assess the corrosion rate in-situ and determine the corrosion risk at the time of testing. The current densities were also much less than that used for the design life estimates suggesting that the anodes will last longer than the estimated 30years.

Considering the above, was proposed that topical corrosion rate testing and half-cell potential measurements would be needed to determine the effectiveness of the system and assess the corrosion risk trends over time.

5 CONCLUSIONS

The use of hybrid anode systems offers a potential alternative for the management of corrosion risk for reinforced concrete bridge structures, especially those located in remote or regional areas where it may be unpractical to install and maintain ICCP systems. When constructing hybrid anode systems, it is important to consider the construction sequencing and the impact it can have on the impressed current phase of the commissioning. It was apparent that the resistivity of the concrete and grout surrounding the anodes has a significant impact on the rate at which the anode can pass charge. The lack of a specific criteria to assess the performance of hybrid anodes and published data from real structures makes it difficult to determine their effectiveness beyond the initial impressed current phase. Corrosion rate monitoring in concrete is a feasible solution; however, the practical application is highly variable and can be very difficult to implement consistently to determine trends.

6 REFERENCES

- Broomfield, John P, Corrosion of Steel in Concrete: Understanding, Investigation and Repair, 2nd Edition: Taylor & Francis London 2007
- Christodoulou, C., Glass, G., Webb, J., Austin, S., Goodier, C. (2010) “Assessing the long term benefits of Impressed Current Cathodic Protection” Corrosion Science 52 (8) , pp. 2671-2679.
- Glass, G.K., Hassanein, A.M. (2003) “Surprisingly effective cathodic protection” Journal of Corrosion Science and Engineering.
- Glass, G K. Robert A C and Davidson N (2008) “Hybrid Corrosion Protection of Chloride-Contaminated Concrete” Proc. Of the Institute of Civil Engineers, Construction Materials 161 (CM4), pp 163-172.
- Green, W K (2001), “Australasian Experiences with Cathodic Protection of Concrete Marine Structures”, Proc. 15th Australasian Coastal and Ocean Engineering Conference and 8th Australasian Port and Harbour Conference, Gold Coast, 25-28 September.

- Green,W, Katen, J and Dockrill, B, What does “Cp” Mean Now for Steel in Concrete?, Proc. Australasian Corrosion Association Conference, Corrosion & Prevention 2017, Sydney
- Grapiglia J P and Green, W K (1995), “Recent Developments in Cathodic Protection Systems for Reinforced Concrete”, Proc. Australasian Corrosion Association Conference ’95, Perth, November.
- Wyatt, B (1994), “CP Options, Design and Cost”, Cathodic Protection of Reinforced Concrete, Institute of Corrosion Seminar, Glasgow, 5 October.

7 ACKNOWLEDGEMENTS

The Author would like to acknowledge the support and input during the project from Nimal Jayasekera of Main Roads Western Australia, Arash Groban of Aecom Australia Pty Ltd, and Fulton Hogan Pty Ltd.

8 AUTHOR BIOGRAPHY

Liam Holloway, Principal Engineer, MEnD Consulting Pty Ltd. Liam Holloway has 18 Years of experience as a materials engineer specialising in durability and corrosion. His work traverses key infrastructure sectors including marine, mining, defence and energy. Liam completed his PhD in the field of corrosion inhibition and monitoring for reinforced concrete structures at Monash University. Following this he has worked in both the consulting and contracting fields with a focus on asset condition assessment, remediation and maintenance. Liam has been involved with the design, installation, and monitoring of numerous reinforced concrete cathodic protection systems for bridges structures across Australia