The world's first hybrid corrosion protection systems for prestressed concrete bridges

THE WORLD'S FIRST HYBRID CORROSION PROTECTION SYSTEMS FOR PRESTRESSED CONCRETE BRIDGES

C. Christodoulou[1], R. Kilgour[2]
[1] AECOM UK [2] AECOM New Zealand

SUMMARY: The Kyle of Tongue Bridge in Sutherland, Northern Scotland opened in 1970, has an overall span of 184m consisting of 18 approximately equal spans and carries a single lane dual carriageway. Prestressed concrete beams form the deck, with reinforced concrete pilecaps supported on steel piles. The bridge was patch repaired in 1989 due to chloride induced corrosion. However, inspections from 1999 onwards reported on-going corrosion and structural deterioration. A refurbishment contract was let in 2011 to extend the service life of the structure for a 30 year period by providing corrosion arrest and prevention.

The Tiwai Point Bridge in Invercargill, Southland, New Zealand opened in 1969, has an overall span of 486m consisting of 27 approximately equal spans and carries a single lane dual carriageway. It is comprised of prestressed and post-tensioned concrete beams forming the deck, with reinforced concrete pilecaps supported on prestressed concrete piles. The superstructure was replaced in 2009-2010 due to severe corrosion to the reinforcement.

Hybrid cathodic protection systems were developed and implemented for both structures. For Kyle of Tongue, hybrid cathodic protection was used to arrest existing corrosion activity to the prestressed concrete beams of the superstructure and extend their service life for a 30 year period by providing corrosion arrest and prevention. For Tiwai Point Bridge, a trial hybrid cathodic protection system was developed to provide corrosion prevention to the prestressed concrete piles within the tidal zone with a targeted service life of 50 years. Hybrid electrochemical treatment provides an attractive alternative to other corrosion protection treatments as it combines the power to arrest the corrosion activity with the simplicity and low maintenance requirements of galvanic technologies. It offers a temporary energising phase to arrest corrosion followed by a permanent galvanic mode phase which is particularly beneficial for prestressed concrete structures in order to reduce hydrogen embrittlement risk. This paper provides a summary of the performance of such hybrid electrochemical systems and how they can be advantageously utilised on prestressed concrete structures to extend their service life.

Keywords: Steel, Corrosion, Concrete, Prestressed

1. INTRODUCTION

Many reinforced concrete structures suffer from corrosion damage. Causes include salt ingress into the concrete and carbonation of the concrete. Treating this damage presents problems because of the associated changes in the concrete cover. Corrosion is an electrochemical process and one technology that has been successfully applied to arrest corrosion is a combination of electrochemical treatments termed a hybrid electrochemical treatment. It has provided a cost effective solution on several structures around the world.

This paper reviews the first hybrid corrosion protection systems applied to prestressed concrete structures to arrest and prevent corrosion damage.

2. CORROSION, PROTECTION AND STEEL PASSIVITY

Concrete is normally highly alkaline and steel in this environment is protected by a passive film. Figure 1 shows a section of the potential-pH diagram for iron and its oxides in water [1]. Passive films are not perfect and some reaction of iron and water does occur. This is usually negligible. However, in the presence of chloride ions, hydrochloric acid is produced and localised pitting corrosion results [2]. The production of acid is considered to be an essential feature leading to significant corrosion damage on passive steel [3]. This process is illustrated in Figure 1. The local environment at the steel is moved from a region where insoluble oxides are the most stable product to a region where iron is soluble in the process of corrosion initiation.

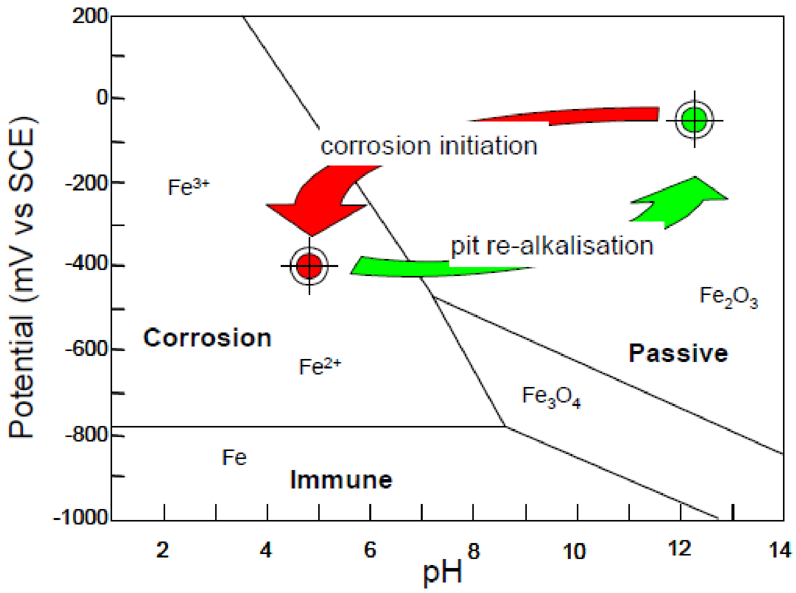

Figure 1 Model of corrosion initiation and arrest showing the stability of iron and its corrosion products.

A powerful and very popular repair technique to arrest deterioration due to chloride induced corrosion is the use of Impressed Current Cathodic Protection (ICCP). The technique relies on the passage of an electric current through the electrolyte to the corroding metal surface and reverses the direction of the electric current produced by the corrosion reactions. It has a proven track record and it has been used worldwide to protect reinforced concrete structures from future chloride induced deterioration [4, 5].

One of the effects of an electrochemical treatment like ICCP is also to produce hydroxyl ions on the steel raising the pH. The local environment at the steel is then moved from a region where iron is soluble to a region where insoluble oxides are the most stable product. This has been proven to provide sustained protective effects to the steel reinforcement even when the protective current has been interrupted and chloride contamination remains [6, 7] This re-alkalisation process is also illustrated in Figure 1 and would lead to a restoration in steel passivity. It is termed pit re-alkalisation when localised pitting corrosion is arrested [3]. Such an effect may halt corrosion, or delay its onset in concrete that is contaminated with chloride even when the protective current has been removed and there is no cathodic polarisation at all [8].

However, for prestressed steel the use of electrochemical treatments such as ICCP which requires a continuous application of current for protection, poses a risk of hydrogen embrittlement [9]. The steel becomes brittle due to the absorption of hydrogen so inducing stress corrosion cracking and leading to premature failure of the steel. This effect occurs on high strength stressed steel tendons such as prestressed or post-tensioned tendons.

Standards deal with such risks by limiting the induced change in the potential of the steel reinforcement. For prestressed steel, the potential of the steel is limited to values more positive than -900 mV vs Ag/AgCl/0.5M KCl (Silver/Silver

Chloride) [9]. This limit aims to reduce the amount of hydrogen generated as a result of water hydrolysis during the application of an electrochemical treatment such as ICCP. However the risk to the asset owner remains throughout the long-term use of an ICCP system as monitoring and adjustments are usually undertaken at annual intervals only and this may not be sufficient.

An alternative approach to reduce this risk would be to apply a brief impressed current treatment delivered using an external DC power supply to re-alkalise the acidic corrosion sites. This takes place over a limited duration, typically no more than 3 months.

An analysis of the available literature shows that applied charge densities below 50kC/m^2 would be sufficient to induce a change in the environment at the steel leading to the arrest of a corrosion process in chloride contaminated concrete [10 – 12].

Such a charge may be delivered using a sacrificial metal as an impressed current sacrificial anode. Thus the temporary electrochemical treatment (initial energising phase) may be delivered in a relatively short period using a sacrificial (galvanic) anode and a power supply. Following the initial energising phase, the anodes are connected in a galvanic cell arrangement to the reinforcement and a galvanic current is delivered from the anodes to ensure sustained steel passivity. Galvanic protection is low maintenance and requires no user input to function. This two-phase treatment is referred to as a hybrid electrochemical treatment [13, 14].

The use of a hybrid electrochemical treatment on the structures described below was advantageous as: i) it combined the power of a traditional electrochemical system to arrest corrosion activity with the simplicity and low maintenance requirements of galvanic technologies, ii) corrosion activity is arrested immediately through a temporary energising phase, iii) overall it presents a lower risk of hydrogen embrittlement which is advantageous for prestressed concrete structures, iv) it negates the need for permanent power supplies and associated annual inspection and maintenance costs, v) it has reduced access requirements for installation and monitoring, vi) it includes a feature for future re-energisation and vii) it presents significantly reduced risks of electrical short-circuits.

3. THE STRUCTURES

3.1 Kyle of Tongue Bridge, Scotland, UK

The Kyle of Tongue Bridge in Sutherland, Northern Scotland carries the A838 road across the estuary of Tongue. It opened in 1970 and has an overall span of 183.8m and consists of 18 approximately equal simply supported spans. The bridge width is 8.5m consisting of a single 5.5m wide carriageway with two lanes and 1.2m and 1.8m wide respectively footpaths.

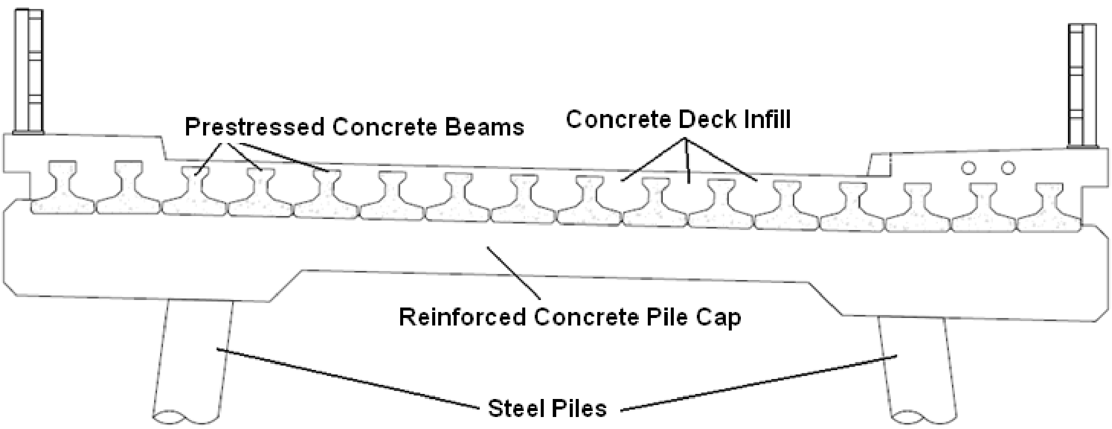

Figure 2 Typical structural cross section of the Kyle of Tongue bridge, UK.

The deck spans are formed by a composite slab of 17 No. precast prestressed concrete inverted T-beams with in-situ concrete infill, and these sit on rubber pads on bearing shelves at all of the in-situ pile caps (Figure 2). The substructure is formed of pairs of long raking hexagonal steel piles capped with in-situ reinforced concrete pile capping beam referred to herein as a pile cap. The bridge was repaired in 1989 due to chloride induced corrosion. However, inspections from 1999 onwards reported that corrosion was still continuing both on the prestressed concrete beams and the reinforced concrete pile caps with evident structural deterioration (Figure 3).

Chloride sampling throughout the structure indicated chloride concentrations exceeding 1% by weight of cement at the depth of reinforcement which indicates a high risk of corrosion. In some cases, chloride concentrations exceeded 2% by weight of cement. With regards to carbonation, depths were in generally low and there were no instances where they reached the depth of steel.

Figure 3 Typical chloride induced deterioration of the prestressed concrete beams

3.2 Tiwai Point Bridge, New Zealand

The Tiwai Point Bridge in Invercargill, Southland, New Zealand opened in 1969, has an overall span of 486m consisting of 27 approximately equal spans, width of 7.3m and carries a single lane dual carriageway. The deck spans are formed by a composite reinforced concrete slab with 4 No. precast prestressed and post-tensioned concrete I-beams with in-situ concrete infill, and these sit on rubber pads on bearing shelves at all of the in-situ pile caps (Figure 4). The substructure is formed by 7 prestressed concrete piles capped with in-situ reinforced concrete pile capping beam referred to herein as a pile cap.

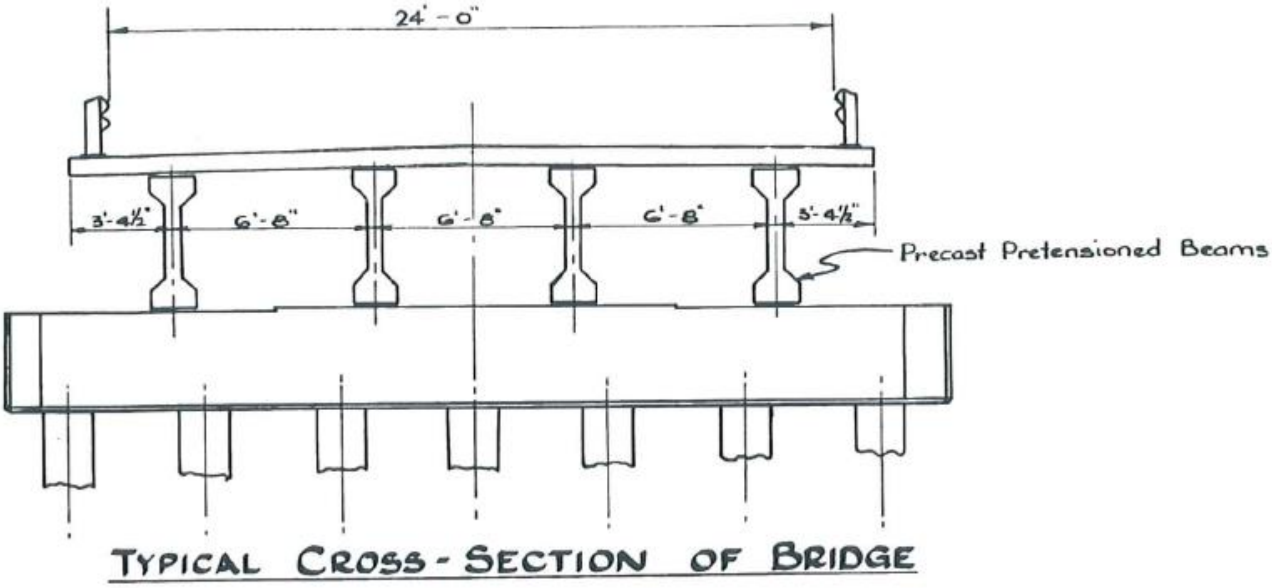

Figure 4 Typical structural cross section of the Tiwai Point bridge, NZ.

The superstructure was replaced in 2009-2010 due to severe corrosion of the reinforcement (Figure 5). The substructure was retained as it was considered to be in fair condition. However, the prestressed piles had high residual levels of chloride contamination and surface cracking. This suggested that corrosion may have progressed to its propagation phase which is the most destructive.

Figure 5 Typical chloride induced deterioration of the superstructure.

4. METHODOLOGY

This section describes the installation procedure, materials used, testing methods and criteria for assessing the performance of the hybrid electrochemical treatment.

4.1 Installation

Only physically deteriorated concrete was required to be removed from the prestressed concrete beams. Hybrid anodes 18mm in diameter and 37mm long were installed in pre-drilled cavities at approximately 300mm centres. The hybrid anodes were installed between the corrosion affected prestressing tendons of each beam. The pre-drilled cavities were filled with proprietary low strength putty to fully cover the anodes and provide separation from the repair concrete (Figure 6).

The hybrid anodes included an integral titanium wire to facilitate the delivery of an impressed current and were connected in a series for each repair. Each series of anodes for the individual repairs was terminated in a junction box which also facilitated a connection to the steel reinforcement. This provided a convenient location to connect them to the temporary power supply for delivering the initial current treatment and later connecting them together in a galvanic cell.

Figure 6 Typical hybrid anode installation on a prestressed concrete beam

4.2 Testing

The assessment of the performance of the hybrid anodes was based on the following:

- Corrosion rates;
- Potential measurements;

Corrosion rates are commonly measured using the polarisation resistance method and they are usually expressed as a current density, a rate of weight loss or a rate of section loss [15, 16]. A corrosion current density of 1 mA/m^2 is approximately equal to a steel section loss of 1 µm/year. In general, corrosion current densities higher than 1–2 mA/m^2 are considered to be significant.

Corrosion current densities are calculated based on the applied current and the achieved potential shift. A small current density applied to the steel produces a steel potential shift and a voltage drop (IR drop) through the concrete [6]. The potential shift and applied current density are inserted into the Butler–Volmer equation, which provides the basis for polarisation resistance theory, to calculate the corrosion current density (Figure 7). It has previously been shown that acceptance criteria based on low steel corrosion rates are strongly related to acceptance criteria based on a minimum potential shift [17].

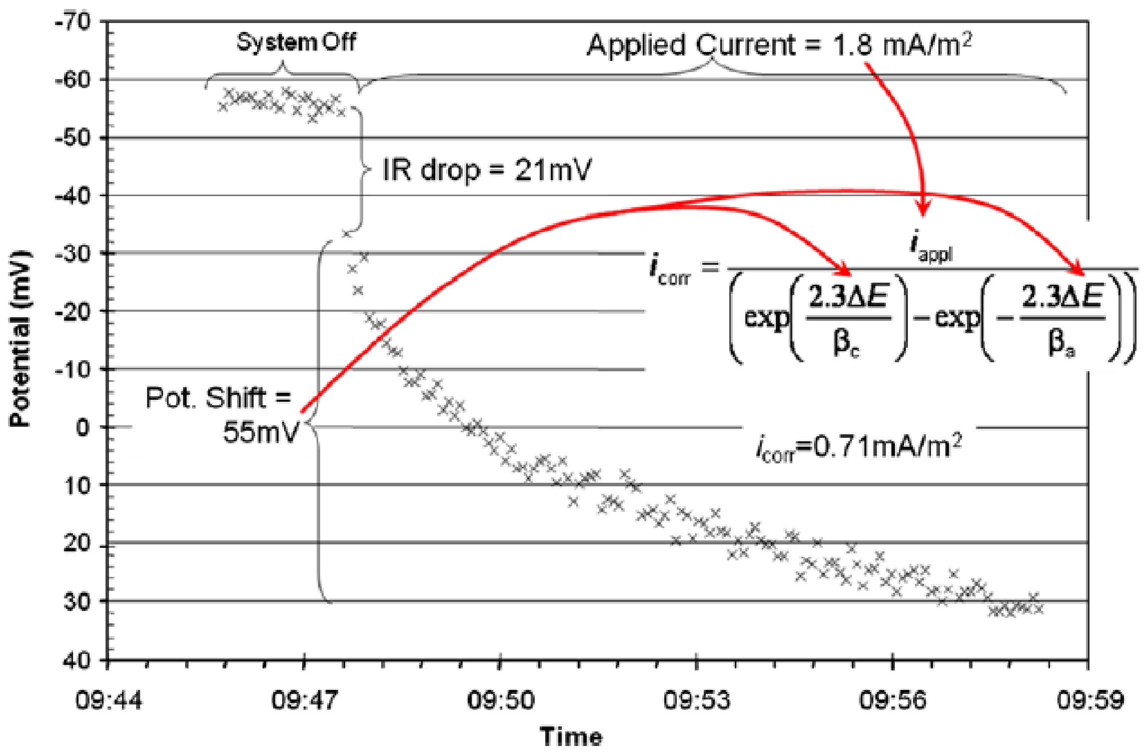

Figure 7 Example corrosion current density calculation [6]

Measuring steel potentials against the potential of a standard reference electrode is a well established non-destructive monitoring technique [18, 19]. Following the application of an electrochemical treatment, steel potentials should move towards less negative values. Such an approach is adopted by Australian Standards [20].

Permanent MnO_2 (manganese dioxide) reference electrodes were embedded within the repairs at four locations which presented the highest corrosion risk based on an initial potential mapping of the area. Readings of steel potentials were also taken after the initial high charge treatment had been completed and the anodes have been switched to galvanic mode.

4.3 Performance criteria

The hybrid corrosion protection system installed on the two structures was designed to provide an initial charge sufficient to arrest corrosion and to provide adequate current to maintain passivity for the remainder of the service life. However, it has also been designed to enable an additional impressed current charge later during service life should monitoring data so determine that this is necessary. On this basis, the following criteria were set for assessing its performance:

- A minimum charge to the reinforcement of 50kC/m^2 (Commissioning Criterion);
- During the impressed current phase of the treatment, the potential of prestressed steel shall not be driven more negative than -900mV with respect to Ag/AgCl/0.5M KCl (Silver/Silver Chloride) electrode (Commissioning Criterion);
- The corrosion rate, measured at locations of high corrosion risk, after the initial impressed current phase and system depolarization should be less than 2mA/m^2;
- The anodes shall be installed in such a way that there is capability for future impressed current treatment phases during the system life.

5. RESULTS

As the Tiwai Point Bridge, NZ repair contract had just started, there were no available data for reporting. As such, the results presented below relate to the Kyle of Tongue Bridge, UK.

Figure 8 illustrates typical monitoring data for the charge density delivered by the hybrid anodes on the repair of prestressed concrete beams. The minimum charge density was set at 50 kC/m^2 and was delivered over a period of 8 weeks or approximately 60 days.

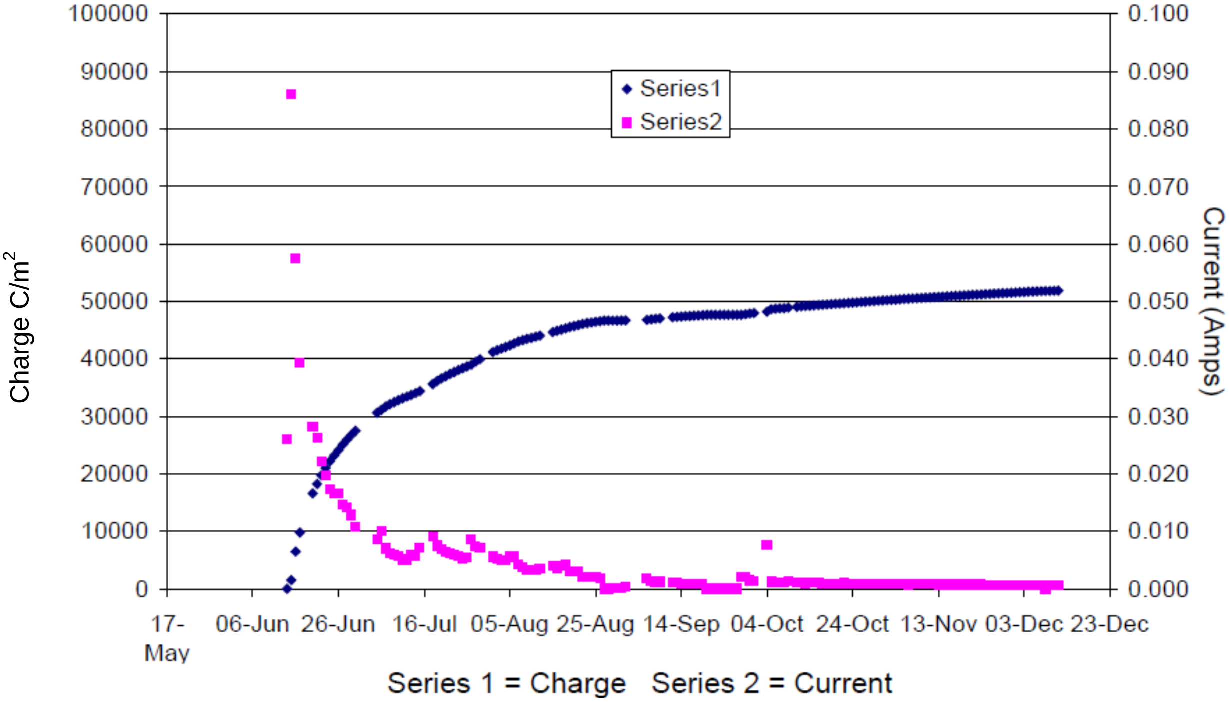

Figure 8 Typical charge density and current applied to the repair of prestressed concrete beams.

In some cases, more than 50 kC/m^2 were delivered to the steel reinforcement. The charge delivered depends on factors such as the aggressive nature of the environment and under these conditions, the charge is delivered easier. Such an occurrence is illustrated in Figure 9.

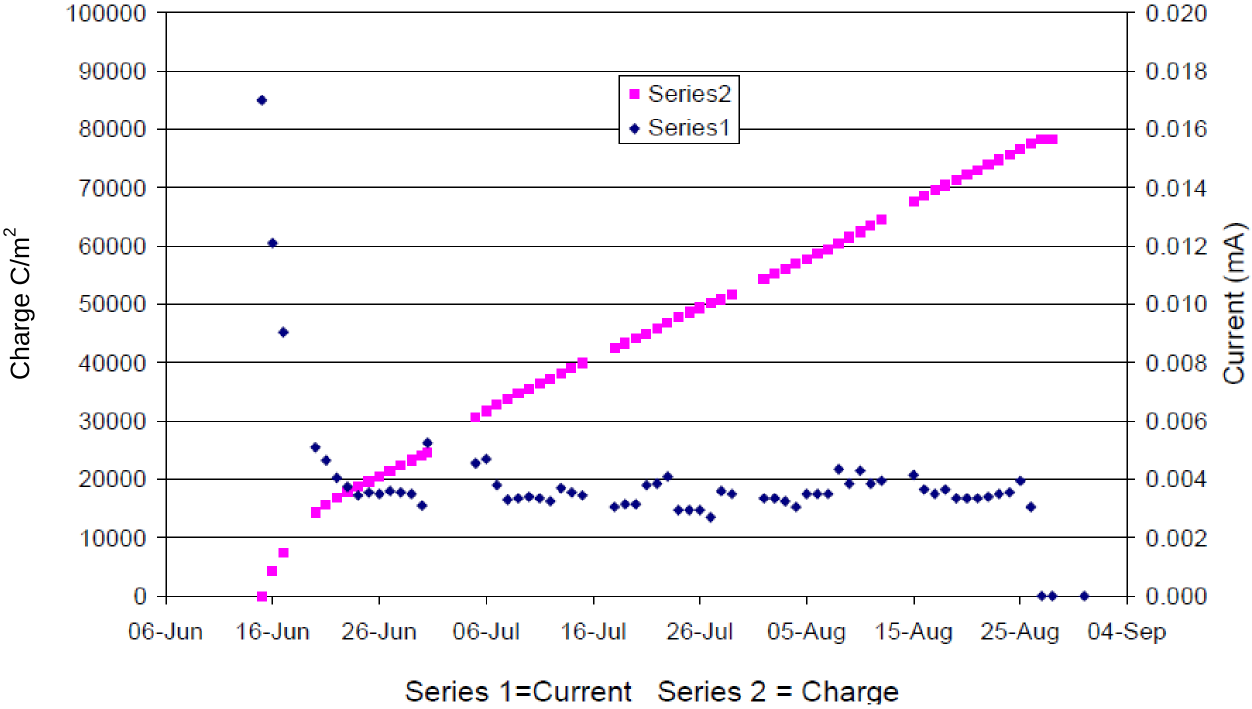

Figure 9 Occasion where higher charge density was delivered to the reinforcement .

Figure 10 illustrates the corrosion current density of four monitoring locations before and after the application of the treatment. It can be observed that in all four cases the corrosion rate dropped below the required threshold and has since remained below it.

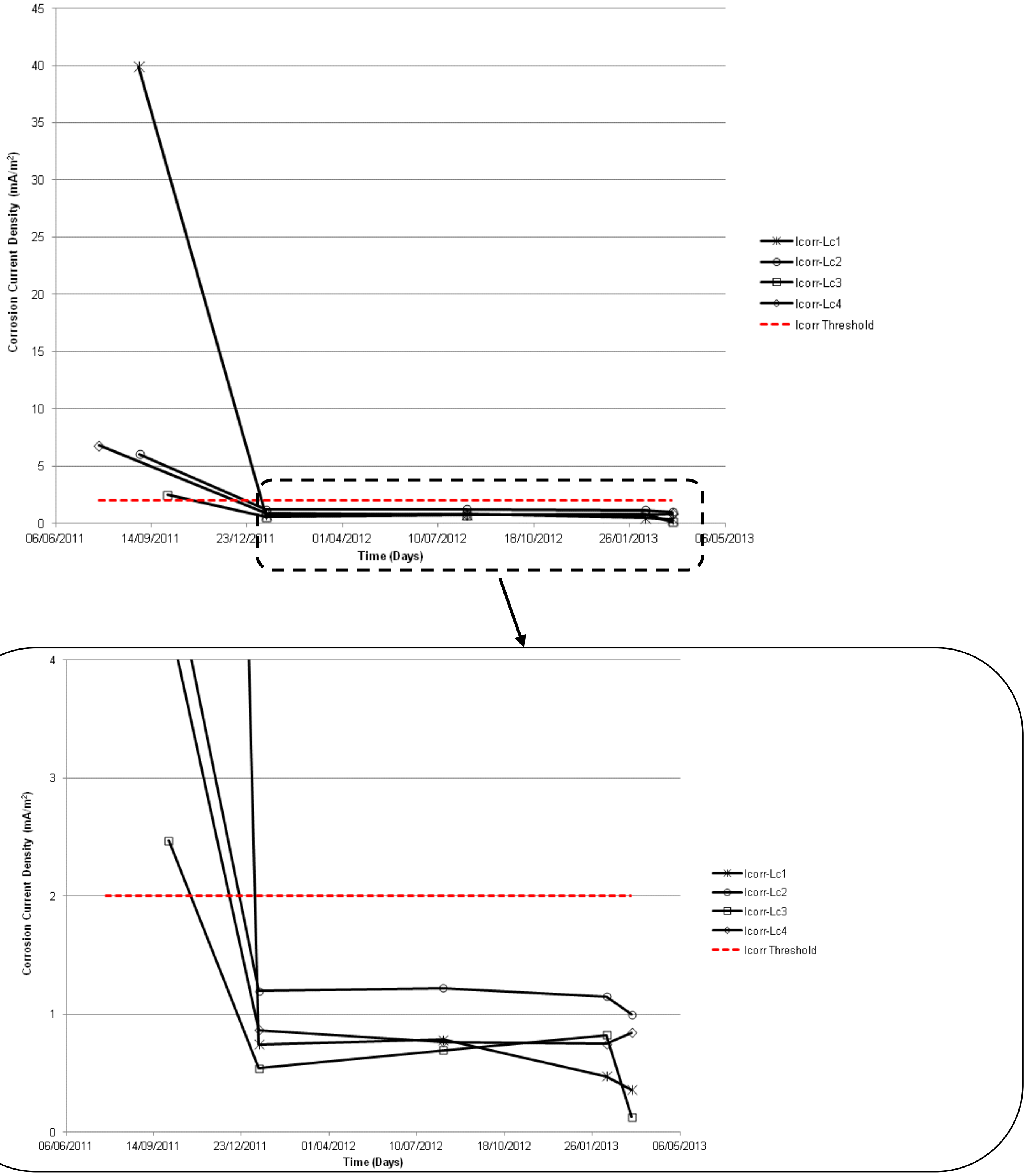

Figure 10 Corrosion rates before and after the application of the hybrid cathodic protection treatment.

6. DISCUSSION

Hybrid cathodic protection is an attractive alternative to traditional electrochemical treatments. In this particular case, it has been successfully applied to arrest corrosion of prestressed concrete elements. The initial high charge treatment was only over a brief period of time (typically 8 to 12 weeks) and took place during the refurbishment works on the bridge, i.e. at a time where the application can be continuously monitored. Daily readings of steel pontetials, voltage and current applied indicated that the potentials during the initial treatment never exceed the limits for prestressed steel and the minimum required charge was delivered at each location [9]. This presents a significant reduction of embrittlement risk when compared to traditional electrochemical treatments.

The corrosion monitoring data shows that the use of hybrid anodes with an initial brief high charge electrochemical treatment resulted in a substantial decrease in the corrosion rate, to a point where the prestressing tendons in the repair areas can now be considered to be passive.

Following the initial high charge treatment, low density galvanic cathodic protection has been sufficient to maintain the corrosion rates below the required threshold. Monitoring of the steel potentials over a period of up to 600 days has also confirmed that the steel is passive. It has been observed that over-time steel potentials have been moving towards more positive values which is an indication of steel passivity. Most importantly, passivity has been maintained despite the continuous exposure to an aggressive marine environment.

7. CONCLUSIONS

It can be concluded that:

- Hybrid corrosion treatment can be successfully applied to prestressed concrete and it is an attractive alternative to traditional electrochemical treatments.
- Following the application of the brief high current electrochemical treatment, corrosion rates have dropped below a threshold value of 2 mA/m^2 and have remained as such since.
- Passivity has been maintained over a period of 600 days despite the continuous exposure of the bridge to an aggressive marine environment.

8. REFERENCES

[1] Pourbaix M. 1990, Thermodynamics and Corrosion, Corrosion Science, 30, pp. 963 – 988.

[2] Glass G.K., Reddy B. and Clark L.A. 2007, Making reinforced concrete immune from chloride corrosion, Proceedings of the Institution of Civil Engineers, Construction Materials, 160, pp. 155 – 164.

[3] Glass G.K., Davison N. and Roberts A. 2008, Hybrid Electrochemical Treatment Applied To Corrosion Damaged Concrete Structures, Transportation Research Board, 87th Annual Meeting, Washington DC.

[4] Broomfield J.P. 2007, Corrosion of steel in concrete: understanding, investigation and repair, 2nd ed., UK: Taylor & Francis.

[5] Concrete Society 2011, Technical Report 73, Cathodic Protection of Steel in Concrete, Surrey.

[6] Christodoulou C., Glass G., Webb J., Austin S. and Goodier C. 2010, Assessing the long term benefits of Impressed Current Cathodic Protection, Corrosion Science, 52, pp. 2671 – 2679 DOI: 10.1016/j.corsci.2010.04.018

[7] Christodoulou C., Goodier C., Austin S., Glass G. and Webb J. 2012, On-site transient analysis for the corrosion assessment of reinforced concrete, Corrosion Science, 62, pp. 176 – 183 DOI information: 10.1016/j.corsci.2012.05.014

[8] Christodoulou C, Goodier C, Austin S, Webb J, Glass G, Diagnosing the cause of incipient anodes in repaired reinforced concrete structures, Corrosion Science, 69 (2013), pp. 123 – 129.

[9] British Standards Institution, 2012. BS EN ISO 12696:2012, Cathodic protection of steel in concrete, London: BSI.

[10] Glass G. K. and Buenfeld N. R. 1995, On the current density required to protect steel in atmospherically exposed concrete structures, Corrosion Science, 37, pp. 1643 - 1646.

[11] Polder R.B., Peelen W.H.A., Stoop B.T.J and Neeft E.A.C. 2009, Early stage beneficial effects of cathodic protection in concrete structures, Eurocorr 2009, Paper 8408.

[12] Glass G. K., Roberts A. C. and Davison N. 2004, Achieving high chloride threshold levels on steel in concrete, Corrosion 2004, NACE, Paper No. 04332.

[13] Glass G, Christodoulou C and Holmes SP, 2012, Protection of steel in concrete using galvanic and hybrid electrochemical treatments, IN: Alexander, M.G. et al. (eds.), Concrete Repair, Rehabilitation and Retrofitting III -

Proceedings of the 3rd International Conference on Concrete Repair, Rehabilitation and Retrofitting, ICCRRR 2012, pp. 523 – 526.

[14] Glass G, Christodoulou C, Towards rendering steel reinforced concrete immune to corrosion, Australasian Corrosion Association 2012 Annual Meeting, 11-14 November 2012, Melbourne, Australia, 2012, paper 159, 11p.

[15] Polder R., Tondi A. and Cigna R., Concrete Resistivity and Corrosion Rate of Reinforcement, TNO Report 93-BT-r0170, TNO Delft, 1993.

[16] Andrade C. and Alonso C. 2004, Test methods for on-site corrosion rate measurement of steel reinforcement in concrete by means of the polarisation resistance method, RILEM TC 154-EMC: electrochemical techniques for measuring metallic corrosion, Materials and Structures, 37, pp. 623–643.

[17] Glass, G. K., Hassanein, A. M. and Buenfeld N. R. 1997, Monitoring the passivation of steel in concrete induced by cathodic protection, Corrosion Science, 39(8) pp. 1451-1458.

[18] American Society for Testing and Materials 2009, ASTM C 876 - 2009, Standard Test Method for Corrosion Potentials of Uncoated Reinforcing Steel in Concrete, West Conshohocken, Pennsylvania, USA.

[19] Concrete Society 2004, Technical Report 60, Electrochemical tests for reinforcement corrosion, Surrey, UK.

[20] Australian Standards 2008, AS 2832.5, Cathodic protection of metals – Steel in Concrete Structures.

9. AUTHOR DETAILS

.

Christian Christodoulou is a Principal Engineer and Corrosion Consultant at AECOM, UK with experience in materials technology, rehabilitation of structures, structural engineering and design. Rehabilitation techniques that have been studied and evaluated and used include various forms of cathodic protection, various temporary electrochemical treatments, galvanic protection, corrosion inhibitors, coatings (including hydrophobic treatments), dehumidification of suspension bridges and novel combinations of these techniques. He is a final year Engineering Doctorate student at Loughborough University.

.

Rob is a Principal Consultant at AECOM and leads the Advanced Materials practice in New Zealand.

He has broad knowledge and experience in delivery of projects and specialist advice to the property, urban development and infrastructure sectors in Australia, New Zealand and the Middle East.

He is a trusted advisor among his peers on issues related to:

- Condition assessment
- Concrete repair
- Durability of materials
- Cathodic Protection.