REDUCING THE MAINTENANCE COSTS AND EXTENDING THE LIFE OF REINFORCED CONCRETE STRUCTURES USING HYBRID CORROSION PROTECTION SYSTEMS – EXAMPLES FROM UNITED KINGDOM, AUSTRALIA AND NEW ZEALAND

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SUMMARY

Asset owners are increasingly seeking extensions of service life from existing structures and increasing returns on investment from maintenance expenditure. Where long term steel reinforcement corrosion protection is required cathodic protection is generally seen as the highest performing solution. Hybrid cathodic protection systems are increasingly seen as a preferred alternative to impressed current systems as they can provide up to fifty years of corrosion protection at a lower lifetime cost. This paper reviews the corrosion control strategies available to asset owners and illustrates projects where hybrid cathodic protection is providing long term corrosion protection in aggressive environments. Forthcoming hybrid cathodic protection projects in New Zealand are discussed.

INTRODUCTION

Reinforced concrete is widely recognised as a versatile and very durable construction material. Improvements in concrete mix design and construction practice are enabling engineers to design reinforced concrete structures with increasingly long design lives. With good concrete mix design, sufficient reinforcement cover and good construction planning design lives of up to 300 years are now believed to be achievable (Hart & Connal, 2012).

Nevertheless a large proportion of New Zealand’s reinforced concrete infrastructure is more than 50 years old (NZTA, 2011) and does not meet current durability requirements (Rogers et al 2012). There is increasing demand for concrete repairs, improvements in the durability of existing structures and extensions of service lives. The reasons for concrete deterioration are well understood (Plum, 1990). Since the 1980’s considerable progress has been made in understanding how to most effectively repair and protect structures suffering from, or expected to suffer from, concrete deterioration. Repair methodologies and material specifications, such as EN1504 Products and systems for the protection and repair of reinforced concrete have been developed to provide asset owners and Engineers with robust guidance on how to cost effectively manage reinforced concrete deterioration (Tanner et al, 2012). Asset owners are using this knowledge to obtain increasing value for money from their maintenance expenditure. In addition there is increasing demand for higher performing corrosion management and corrosion protection systems to provide long term reinforcement corrosion protection and control.
OPTIONS AND STRATEGIES FOR MANAGING STEEL REINFORCEMENT CORROSION

The asset owner has a wide range of options for managing reinforcement corrosion. The most basic is to patch repair the spalling that results from reinforcement corrosion. This approach invariably entails a regular maintenance cycle as it only addresses the symptoms of the deterioration and not the causes. Moreover, despite a repair being executed to a high standard, the incipient anode effect frequently drives rapid deterioration of concrete immediately adjacent to the repair. The incipient anode effect arises from the reinforcement corrosion being an electrochemical process with an anode and a cathode (figure 1). Corrosion occurs at the anode and eventually results in spalling. Localised cathodic protection occurs at the cathode despite it being located in a potentially corrosive environment. Undertaking patch repair eliminates the electrochemical process, removing the anode and cathode. The loss of the localised cathodic protection enables corrosion to initiate at the previous cathode site. As a large electrochemical potential difference exists between the steel in the uncontaminated fresh patch repair and the steel in the adjacent contaminated concrete the corrosion is frequently rapid and signs of deterioration are quickly evident.

Another approach to address the incipient anode effect is to apply a corrosion inhibitor around the periphery of the repair. These delay the onset of corrosion and reduce the rate of any corrosion that does occur (Richardson M.G., 2006). The lifetime of surface applied corrosion inhibitors in concrete is typically ten to fifteen years. They are generally effective for chloride concentrations up to 1.0% chloride by weight of cement at the reinforcement depth.

The above strategies provide significant improvements in the effectiveness of the concrete repair cycle, delaying the time to the next round of patch repairs and reducing the amount of repair to be undertaken. However even greater value can be achieved by protecting not just against incipient anode corrosion but also against the wider development of corrosion over the rest of the structure. Hydrophobic impregnations and surface coatings can be applied over large areas of the structure to prevent chloride or carbon dioxide ingress and when applied in good time prevent the carbonation or chloride penetration from reaching the reinforcement and initiating corrosion. Even if corrosion has been initiated the drying of the structure arising from their application will reduce the rate of corrosion. Corrosion inhibitors may be cost effectively applied over large areas to delay corrosion initiation and slow the rate of corrosion that does occur. When application of a hydrophobic impregnation follows the application of the corrosion inhibitor corrosion may be halted (Richardson, M.G.)
Realkalisation (for protection against carbonation induced corrosion) and desalination (for protection against chloride induced corrosion) can halt corrosion and provide long term protection against it being reinitiated. Typically a coating is applied after these treatments to prevent repeat carbonation or chloride ingress. Although many successful realkalisation and desalination projects have been undertaken worldwide it is often found to be difficult to reduce the chlorides to below the generally accepted corrosion threshold. Often this is due to the chlorides being chemically bound to the cement phase of the concrete. A ‘leap of faith’ is often required to judge chloride extraction projects as successful. Unsurprisingly realkalisation and desalination have not been adopted in New Zealand.

Until recently the most effective technique for achieving reliable widespread corrosion protection of contaminated concrete has been impressed current cathodic protection. This involves installation of an anode on the concrete surface (often an embedded mesh or ribbon) connected to the positive side of a permanently installed power supply (figure 2). The steel reinforcement is connected to the negative side of the power supply. Throughout the lifetime of the system an impressed current is passed preventing reinforcement corrosion from occurring. Impressed current cathodic protection systems must be designed by a suitably qualified cathodic protection engineer. In addition regular monitoring and adjustment of the power supply is required to ensure that a suitable shift in electrochemical potentials is achieved. The ongoing monitoring, adjustment, and maintenance of the impressed current cathodic protection system results in significant ongoing costs to the asset owner and, with the high installation cost, results in a high lifetime cost. Nevertheless a properly installed and maintained impressed current cathodic protection system remains an attractive way to manage reinforcement corrosion for many high value structures with long remaining service lives.

Due to concerns about the risk of hydrogen embrittlement impressed current cathodic protection systems are often regarded as unsuitable for prestressed concrete structures, precluding its use on a large proportion of New Zealand’s infrastructure (Christodoulou & Kilgour, 2013)

**HYBRID CATHODIC PROTECTION SYSTEMS**

Hybrid cathodic protection systems combine the benefits of galvanic protection, realkalisation and cathodic protection without the need for permanent power supplies, ongoing monitoring and maintenance.
Hybrid systems use an array of discrete galvanic anodes connected to the steel reinforcement. These are operated in two distinct phases. The first phase involves temporarily connecting the anode string and reinforcement bar to a low voltage (6V or 12V) direct current power supply (figure 3). The objective is to passivate the steel reinforcement by passing 50 KC of electrical charge per square metre of steel reinforcement. Seven to fourteen days is typically required for this. At the end of this period the power supply is removed and the second phase of operation begins with the system operating galvanically. In this phase the anodes are connected directly to the steel reinforcement. No further use of the power supply is required.

![Figure 3 - diagram of a hybrid cathodic protection system with temporary power supply](image)

The initial impressed current phase is sufficient to restore the passivity of corroding steel reinforcement in the most aggressive of corroding environments. Once completed only a very small electrical current is required to maintain steel passivity and this is supplied in the second phase of the operation by the galvanic anodes (Christodoulou & Kilgour).

A hybrid system will provide the same reinforcement corrosion protection, reduction in maintenance costs and service life extension as an impressed current cathodic protection system, at a lower lifetime cost, and will operate in this way for up to 50 years. In addition the system can be designed to avoid the risk of hydrogen embrittlement and is therefore fully compatible with prestressed concrete structures.

Hybrid cathodic protection systems have been successfully used for nine years with projects in Europe, Middle East and Australasia. Hybrid systems have been specified for use in projects in New Zealand.

**WHITEADDER BRIDGE PROJECT, UNITED KINGDOM**

The earliest hybrid cathodic protection systems were installed in the United Kingdom in 2005. These early projects have been monitored since installation and confirm efficacy of corrosion control and performance in line with those observed in laboratory investigations (Holmes et al, 2011).

One such early project is Whiteadder Bridge near Berwick on Tweed. The bridge carries a road over Whiteadder Water, a tributary of the River Tweed. It was built in 1973 to replace a temporary bridge in place since the original 1868 stone built structure was washed away in the Great Flood of 1947.
The bridge was suffering corrosion damage to the piers due to de-icing salt leakage from the bridge deck. Testing showed that chloride salts had diffused through the cover concrete over the majority of the structure with resultant steel reinforcement corrosion. The client installed a hybrid cathodic protection system to protect the piers from further corrosion induced damage for a minimum 30 year period.

A total of 2500 hybrid anodes were installed onto the structure over a 14 week period. A remote monitoring system was installed in order to confirm on-going performance. A series of twelve manganese oxide reference electrodes were installed in two zones at different elevations on the west pier. These electrodes were wired back to a central data logger which could be downloaded remotely using a gsm modem with power supplied by a solar panel. Thus detailed and long term data from buried reference probes could be obtained.

Data taken over a period of 6 years is shown in figures 6, 7 and 8. The current output is higher in the lower zone where the concrete has continually higher moisture content, and is also dependent to some extent on temperature (Holmes, 2009).

The steel potentials indicate passive steel over a prolonged period after the initial impressed current treatment (Broomfield, J.P., 1997). Steel potentials from the lower zone are slightly more negative – reflecting the increased moisture content in this area. All the reference cell locations demonstrate similar behaviour indicating that a relatively homogenous environment around the steel reinforcement has been generated following the hybrid treatment.

The current and potential data show occasional spikes in values. These are associated with flood events at the bridge – when the river floods, the water is in contact with the piers. This increases moisture content and as a consequence the current output of the hybrid system increases to counter any potential corrosion activity. This ‘responsive behaviour’ means that anode consumption decreases when corrosion conditions are relatively benign and increases when local conditions become more aggressive (Glass et al, 2008).
Figure 6 - Current output v time for 2 monitored zones

Figure 7 - Steel potentials from upper monitored zone

Figure 8 - Steel potentials from lower monitored zone
The Curragh Coal Mine is an open-cut coal mine located 30 km north of Blackwater in Central Queensland, Australia. One of the mine's several reinforced concrete thickener tanks was suffering extensive chloride attack to the reinforcing steel due to the high levels of chloride in the coking coal (figure 9). The tank was built in the late 1970's and has been subjected to high chloride levels throughout its service life. The tank is 85 metres in diameter and 3 metres high.

Concrete maintenance works had been ongoing and the mine manager was looking for a permanent maintenance free solution to the corrosion issues with the tank. Concrete repair and maintenance works were programmed during a periodic shut down of the plant but due to the operation of the thickener tank being critical to the operation of the mine the time available for remedial concrete works to the tank was limited.

A Hybrid Anode system was proposed as a cost effective low maintenance repair option that could extend the service life of the thickener tank by 30 years with minimal future disruption to operations. An additional benefit of the hybrid anode system was that the hybrid anodes could be installed while the mine was in operation and the thickener tank was live – reducing the required shut down period.

Under shut down conditions conventional concrete repair, hydro demolition, repairing of corroded reinforcing steel and shotcreting were undertaken. The thickener tank was then brought back into live service minimising the out of service period for the mine operator. The hybrid anode system was then installed. This included;

- Locating steel reinforcement and drilling anode holes
- Cutting chases for reference electrodes and cabling
- Welding negative connections to reinforcing steel
- Installing the hybrid anodes (figure 10)
- Connecting to junction box and monitoring equipment
- A final overlay of shotcrete

A remote monitoring system including forty reference electrodes to monitor corrosion potentials was installed to the thickener tank allowing access to monitoring data via internet connection.

This AU$2.6 million project involved 80m² of hydro demolition and gunite repair and the installation of 10,000 galvanic anodes. The hybrid system has been in operation for over 3 years and is performing well in the extremely corrosive environment that it has been designed for. All of the corrosion rate measurements taken to date show that the steel has become passive and no further chloride induced corrosion has been initiated.
ADOPTION OF HYBRID CATHODIC PROTECTION SYSTEMS IN NEW ZEALAND

In New Zealand impressed current cathodic protection is a small niche market primarily serving the protection of bridges and wharfs. The technique is well known to the owners of such assets. Unsurprisingly hybrid anode cathodic protection systems are now being considered as an attractive alternative – primarily due to their maintenance and monitoring free operation and subsequent lower operational and lifetime costs. Two current projects where hybrid systems have been specified are the Tiwai Point Bridge and the SH16 Causeway.

Tiwai Point Bridge, located in Invercargill is a road bridge constructed in 1969 and comprises 27 reinforced concrete spans with a total length of 486m. The deck spans are formed by a composite reinforced concrete slab with four precast prestressed and post tensioned concrete I beams with reinforced concrete infill. This superstructure was replaced in 2009 due to severe reinforcement corrosion. The substructure is formed from prestressed concrete piles capped with insitu reinforced concrete capping beams. The piles have not been replaced however they exhibit high residual chloride levels and surface cracking and are reported to be subject to Alkali Silica Reaction (ASR).

The initial remedial method proposed for the piles was to provide a concrete encasement. The concern with this approach was that an encasement does not address the underlying corrosion issues on the prestressing strands. A trial hybrid cathodic protection system was proposed as an alternative. Such a system was preferred as it operates at the low current densities required for prestressed steel without exacerbation of ASR. The specified system uses 18mm diameter 37mm long anodes at 300mm centres. This is expected to provide up to fifty years of reinforcement corrosion protection.

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The SH16 Causeway Project involves widening and raising SH16 in Auckland between Great North Road and Te Atatu Interchanges. The route crosses two bridges – the Whau River Bridge and the Causeway Bridge. The Causeway Bridge includes prestressed piles and conventionally reinforced concrete piles. The Whau River Bridge is supported by conventionally reinforced concrete piles. Both bridges are in marine environments and require a limited amount of concrete repair. Inspection of the piles of both bridges indicates significant chloride ingress and a long term corrosion protection strategy is required for some piles.

The selection of a zinc based hybrid anode system for corrosion protection of both prestressed and conventionally reinforced piles at both bridges was based on the following considerations:

- presence of prestressing within the Causeway Bridge piles
- desire for a modular system that could be expanded in future if required
- consistency of design for both prestressed and conventionally reinforced concretes
- desire to minimise the lifecycle operating and maintenance costs for the asset owner

The hybrid protection systems are zoned to address the varied exposure environments encountered on the structures. The systems are expected to be installed by the Causeway Alliance in 2014.
CONCLUSIONS

Asset owners have a wide range of options for managing reinforcement corrosion in concrete structures. Cathodic protection is generally regarded as the most effective method of controlling reinforcement corrosion. However, its high lifetime costs and unsuitability for use on prestressed concrete has limited its adoption.

Hybrid cathodic protection systems combining a short period of impressed current to passivate the steel reinforcement followed by ongoing galvanic protection have overcome much of the limitations of impressed current cathodic protection. Ongoing monitoring and maintenance is not required during the life of the system, reducing the lifetime costs of installations. Systems can be designed to operate in this way for up to 50 years. They are also compatible with prestressed concrete.

Hybrid systems have been adopted worldwide and are currently being adopted in New Zealand, providing New Zealand’s asset owners with an additional attractive option for long term protection of reinforced concrete structures.

REFERENCES


