Future Directions for Designing Low Maintenance Impressed Current Concrete Cathodic Protection Systems

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Abstract

Impressed current cathodic protection (CP) for reinforced concrete structures is a proven technology which can provide long-term corrosion protection solutions for marine structures. This technology has been installed on a large number of structures in Australia over the past 35 years and it is the technology of choice for asset owners for the protection of structures subject to chloride-induced corrosion.

While this technology has proven to be effective for the corrosion protection of reinforced concrete structures, a review of performance and inspections of numerous systems in Australia has led to the conclusion that there are many areas for future improvement. These include optimised designs of CP systems in new concrete structures and the development of systems which can deliver corrosion protection with substantially lower ongoing maintenance costs. The areas for improvement are in materials selection, system design, installation and monitoring of CP systems.

This paper will highlight the key areas for improvement and the lessons learnt from past cathodic protection applications, and will propose a series of recommended changes to current practices that can be considered for implementation in the design and installation of new impressed current cathodic protection systems in concrete.

Keywords

Cathodic Protection; Impressed Current; ICCP; CP System; Acidification

Introduction

Reinforced concrete is a composite material that relies on the high compressive strength of concrete and the high tensile strength of steel for its mechanical performance. Steel has poor corrosion resistance and concrete has good anti-corrosion properties. The hydration process of concrete leads to the formation of hydroxides which raise the pH level of the cement to around 12.5 and provide a stable oxide layer on the steel surface, which prevents the anodic dissolution of the steel. Failure of reinforced concrete is caused by corrosion of the steel reinforcing bars as a result of the destabilisation of the oxide layer. When the passivity of the steel partly or completely breaks down, either as a result of carbonation or chlorides, corrosion may initiate. This means that the electrochemical potential of the steel locally becomes more negative and forms anodic areas, while other portions of the steel with the passive layer intact will act as catchment areas for oxygen and will form cathodic areas.

Due to the substantial economic significance of corrosion problems for reinforced concrete structures, there have been significant attempts from the early 1970s until today to improve the quality of reinforced concrete by changing the material properties of both the steel reinforcement and concrete, and/or by applying corrosion prevention measures during construction. For concrete, improvements include the use of high performance concrete in conjunction with protective coatings, thick concrete cover and the use of corrosion inhibitors. For steel, improvements include the use of stainless steel, galvanized steel and epoxy coated reinforcement instead of, or in conjunction with carbon steel. In various applications where a 100 year design life is specified, cathodic prevention has been applied effectively in many countries including Australia [1].

Irrespective of the material improvements of reinforced concrete, corrosion of the steel reinforcement is still a major durability problem, and in particular, for structures exposed to chloride contamination.

In Australia, electrochemical techniques such as cathodic protection have been utilised as a standard and reliable technique for the long-term corrosion protection of structures situated in marine environments and susceptible to chloride induced corrosion.

A large number of impressed current cathodic protection (CP) systems in concrete have been installed in Australia during the past 35 years. The majority of these systems have been installed in accordance to international standards [2, 3], up until the issue of Australian Standard AS 2832.5 [4].

The international and Australian standards provide general guidelines relating to the assessment and repair of reinforced concrete structures, CP system components, installation procedures, commissioning of systems and the operational criteria for CP systems.

Nevertheless, there are various issues associated with the design and installation of CP systems that are outside the scope of the standards. These issues may have significant implications on the long-term performance and maintenance of the CP systems.

Based on the results of multiple audits carried out by the authors in recent years on various CP systems operating on marine structures in Australia, the majority of the identified problems were mostly related to the functionality and reliability of the control units and durability issues associated with CP system components such as junction boxes and the grout material encapsulating the anodes. We note that while there were numerous identified issues with the CP systems, importantly, for all of the audited structures, there were no major corrosion problems of the steel reinforcement.

It is the author's opinion that due to the above-mentioned issues, the rectification work of the structures protected by CP systems resulted in relatively high maintenance costs, however there was no evidence that the capacity of the CP systems in delivering corrosion protection to the embedded reinforcement was reduced as a result of the current interruption during the rectification period.

This paper will present some of the issues related to CP application and recommend various solutions which may assist in the improvement of future CP system design and installation.

Impressed Current Cathodic Protection (ICCP)

Impressed current cathodic protection (ICCP) is a proven electrochemical technology applied for the protection of reinforced concrete structures. ICCP promotes the development of steel passivity as a result of the production of hydroxyl ions at the steel-concrete interface to stabilise the protective passive film. In addition, the direct effect of CP includes shifting the steel potential to more negative values, which inhibits the corrosion of iron, and moves the chloride ions away from the steel and towards the anode.

When steel corrodes in concrete, the process is comparable to that of a battery. In a battery, electrons are generated because two dissimilar metals are exposed to an acidic solution (paste or gel in practical batteries) that corrodes one metal and creates a harmless reaction in the other. This corrosion reaction at the 'anode' generates electrons that are consumed by the 'cathode'.

For the steel reinforcement that corrodes in concrete, one very small area is the positive pole (anode) and another much larger area is the negative pole (cathode). The corrosion current flows out of the steel at the anode (the corroding part), passes through the concrete and into another part of the steel where there is no corrosion occurring (the cathode). This current flow is called the corrosion circuit and the steel dissolved at the anode forms iron dioxide.

In a practical battery, the electrical connection between positive and negative poles can be disconnected. The circuit is then broken and the dissolution of metal stops.

In concrete, the corrosion circuit is buried in the structure and the electrical current running through the concrete cannot be disconnected. The only method of stopping the current from running through the concrete is to provide new current from an external source via an external anode in/on the concrete. The flow of electrons between the new anode and the reinforcing steel changes the previously positive poles (anodes) into current receivers. Thus, all of the steel reinforcement becomes a negative pole or cathodic, and hence the name 'cathodic protection'.

The application of cathodic protection for concrete structures transforms the environment around the reinforcement over a period of time. The negatively polarised metal surface repels the chloride ions from the steel while the hydroxide ions generate at the steel's surface. These hydroxide ions are responsible for inducing passivity of the reinforcement.

CP System Installation

For cathodic protection (CP) systems installed in concrete structures:

- The embedded components in the concrete include anodes, anode connections, steel connections, cables, conductor bars, reference electrodes and concrete reinstatement materials.

- The components outside the concrete include transformer/rectifier (T/R) units, T/R unit cabinet, junction boxes, cables and conduits.

It is the author's opinion that in Australia, the CP systems that are installed in accordance to current standards do not have major issues associated with the CP components embedded in the concrete, besides the case of grout acidification where ribbon anodes are installed in tidal and splash zones. The design of CP systems has been carried out in such a way that in most cases in the unlikely event of a failure of one anode connection and/or one steel connection in a CP zone, the current delivery to the steel would not be affected as the standards and common design practices allow for multiple connections within each circuit. Generally, in most cases, concrete breakout to rectify CP system components within the concrete has not been common or required.

Problems Associated with CP System Installation

Based on the assessment of a large number of operating CP systems in concrete in Australia, the major and common issues associated with CP systems are as follows:

Grout Acidification of Anodes

In general, the most common CP systems have their anodes installed in slot cuts in the concrete cover (ribbon anode), or in holes drilled into the concrete (discrete anodes). When current is passed at the anode, acid is generated, and this may cause damage to the cementitious material which encapsulates the anode.

SHRP - S - 372 (Cathodic Protection of concrete bridges: a manual of practice [5] indicated that, "*the two major anodic oxidation reactions that take place in concrete involve the evolution of either oxygen or chlorine, as follows:*

$$2H_20 = 02 + 4H^+ + 4\ e^-$$

$$2Cl^- = Cl_2 + 2\ e^-$$

In concrete, which has a relatively high pH value, the chlorine will undergo rapid hydrolysis, expressed as follows:

$$Cl_2 + H_20 = ClO^- + Cl^- + 2H^+$$

Therefore, for either anodic reaction or any combination of the two reactions, one atom of acid (H+) will be generated for the passage of each electron. Experience has demonstrated that if these reaction products are produced at a high rate because of high anode operating current densities, damage to concrete near the anode surface will result. If anode reaction products are generated slowly, they will diffuse into the concrete without causing any problems. Therefore, current density of 10 mA/ft.^{2} (108 mA/m^2) *on the anode surface is usually specified as a maximum".*

In Australia, large sections of the CP systems protecting wharves and bridges are installed in tidal and splash zones and with design current densities not exceeding 110mA/m^2. However, at most of these CP installations, there is evidence of acidification problems occurring in the tidal and splash zones. While in some cases, current dumping (due to poor system zoning design) may have contributed to higher current densities and acidification problems, it appears that in the majority of cases, water ingress to the anode due to poor anode encapsulation detail has been the major contributing factor causing acidification.

There are two main common types of anodes used for the CP systems installed in tidal and splash zones. These are ribbon anode strips and discrete anodes. Grout acidification has been mainly associated with ribbon anode which is installed in tidal and splash zones [5]. There is not enough testing and verification data available regarding grout acidification around discrete anodes, however from our review and experience, the problem is significantly less evident for discrete anodes in concrete.

The occurrence of grout acidification may not have a short-term impact on the performance of a CP system. There is no direct correlation between grout acidification and initiation of reinforcement corrosion in the areas of affected by acidification. This has been noted even after many years from the initiation of the grout acidification problem, it appears that the CP current delivery from the anode is not substantially impacted by the grout affected by acidification.

There is no evidence of any direct correlation between the initiation of grout acidification and anode current density. Grout acidification has been observed in concrete elements operating at low current density while similar elements operating at higher current densities were not affected by grout acidification. Possibly, the direct exposure of the ribbon anode to water is the primary cause of the acidification process initiation. However, the impact of the high anode current density on accelerating the acidification process must be investigated.

There is no evidence of any direct correlation between the grout acidification and the resistivity of the grout material.
There is a direct correlation between grout acidification and the location of anodes. For anodes installed in tidal and splash zones, in nearly all cases of typical anode installation, the problem of grout acidification was evident.

For tidal zone areas, the second stage of grout acidification occurs with the washing out of grout from around the ribbon anode locations. In these cases, the anode will be immersed for a certain period of time every day in salt water subject to tidal movements. The ribbon anode will be operational while immersed in water, and based on the author's experience, no concrete deterioration has been observed in tidal and splash zones as a result of grout acidification, or when the anode is fully exposed without grout. It appears that the partial delivery of the cathodic protection current while the anode is immersed in water may still deliver sufficient cathodic protection current to the embedded steel to stop corrosion initiation. It is important to note that the chloride level in those areas is very high.

There is a direct correlation between grout acidification and poor CP system zoning. If a CP circuit is located in a combined zone of exposure and tidal exposures, in many cases acidification has been evident in the tidal zone. A possible cause is current dumping, which is a result of water ingress to the anode level causing localised high current discharge in isolated locations.

Failure Associated with Water Damage to Junction Boxes and Control Unit Cabinets

Junction boxes which are installed in areas susceptible to water exposure are normally specified with Ingress Protection (IP) suitable for such exposure. However, it is the author's experience that regardless of the IP protection for these enclosures, such protection is likely to be seriously compromised during the design life of the CP system, especially when the junction boxes are installed in an area of high water exposure.

For junction boxes installed in areas of high potential water exposure, the following causes, or a combination of these causes can result in failure:

- Movement in the structure causing physical damage to the junction boxes and conduits;

- Failure of the rubber seal cover of the junction boxes; and

- Failure of the sealant applied around the conduit entries.

Control System Selection

Various types of control systems have been installed in Australia over recent years. These control systems range from manually operated systems, to highly advanced systems with full remote monitoring and control capabilities including remote facilities for depolarisation testing and various levels of alarm functionality. Generally, it has been the more basic, heavy duty manually operated systems which have been more reliable in comparison to remote control systems with a high level of remote control functionality.

The capacity of a CP system to deliver continuous cathodic protection current to a structure is the key and most important requirement of a control system. Regular functional checks of current delivery, in conjunction with yearly testing and adjustment of the system (including an inspection of the structure), is sufficient for the optimum long-term monitoring and maintenance of the CP system.

The failure to select the optimum control system for a particular structure may cause the following:

- Problems with delivering cathodic protection current to the structure, and thus over time reducing the capability of the system to provide corrosion protection to the structure;

- Frequent parts replacement, and;

- Excessive costs for monitoring and maintenance work.

Workmanship Detail During Installation

Poor workmanship may lead to faulty system operation and this may not be recognised until corrosion problems become evident in the structure. The proper manufacturing and installation of anode and steel connections, the correct installation of reference electrodes, anodes (both ribbon and discrete) and systematic testing and establishing of continuity between all embedded rebar within the CP zone, are some of the key issues which may affect CP system operation.

CP System Installation on Live Load Structures

Some CP systems have been installed retroactively to wharf structures under live load operating conditions. In most of these CP applications, gunite material application has been used. This material has been applied in two layers with ribbon anode installed between the layers. Some delamination between the gunite layers may occur during construction as the gunite application is often carried out under live load conditions. Extensive testing for any apparent defects with this type of installation has indicated that in most cases, there is no impact on the performance of the CP system or any consequential damage associated with the corrosion of the reinforcement. Detailed testing at breakout locations on various structures has revealed that the grout encapsulating the anode is fully sufficient to pass the CP current to the embedded reinforcement and to ensure adequate CP system operation.

Testing of the extent of concrete delamination must be carried out and verified for each individual structure to ensure that there is no negative impact on CP system performance.

Anode Material Selection

The primary anode products for concrete CP applications in Australia are ribbon anode and discrete anode. Ribbon anode is produced by numerous manufacturers around the world. All ribbon anodes strips have a similar appearance. It is difficult to make an assessment regarding the suitability of a product based on visual inspection or the information provided by the suppliers in the technical data sheet.

The selection of the anode material will have an ongoing impact on the long-term performance of the cathodic protection system because the anode is the primary material delivering the cathodic protection current to the elements of the structure.

Cathodic Protection Recommended Future Directions

Anode Grout

Grout acidification is a problem area which requires further detailed assessment possibly under a research program. The main areas of assessment may include anode current density, resistivity and material characteristics of the the grout surrounding the anode and the encapsulation methods of the anode. Meanwhile, until such detailed research is carried out, CP systems will require a special design for all areas of anode installation in tidal and splash zones with relation to anode current density, anode embedment details, grout selection and special coating application.

The author has been incorporating such measures in system designs for the past 10 years and it appears that there is a substantial reduction of grout acidification problems as a result of these measures. The measures are as follows:

- The elimination of the use of ribbon anode in tidal and splash zones where possible. Discrete anodes offer a better alternative in these areas.

- Anode design shall be based on a maximum anode current density for ribbon and discrete anode of $110mA/m^2$ of anode surface.

- Use of special CP grout which is specially formulated to minimise acidification (high pH).

- Application of additional cementitious coating on the ribbon anode slot to prevent the ingress of water through the shrinkage cracks that may develop between the grout covering the ribbon anode and the original concrete.

Water Damage to Junction Boxes

In terms of reducing maintenance requirements associated with junction boxes, elimination of junction boxes altogether in areas where the junction boxes will be susceptible to water ingress, or alternatively, permanently sealing the junction boxes with epoxy material or other suitable products should be considered during the design stage. Recent inspections of junction boxes positioned in wet areas reveal the superiority of these approaches in eliminating problems associated with water ingress and damage to the junction box cabling.

Control Systems

With the advancement in technology in the past two decades, it has often seemed logical for asset owners to install increasingly advanced and sophisticated control systems for the monitoring of their CP systems. However, it is important to understand that the improvements that these more advanced systems offer have been somewhat limited. Most of the commercial systems that are currently available (while offering various levels of advanced communication and remote testing functions), may lack the required level of durability, can be complex to operate, difficult to repair, and often require a high level of technical support for monitoring and maintenance. This has led to an increase in the cost of monitoring and maintenance of CP systems to a level beyond what would be normally acceptable for asset owners for the long-term maintenance of their assets.

Assessing the need and the benefit of such systems against the complexity of maintaining and operating them must be carried out for each individual structure. Sophisticated control systems may be suitable for large and complex CP installations located in areas where they can be easily serviced. However, for relatively basic and simple CP installations or CP installations in remote locations, it is likely that such systems will add no value to the efficiency of a long term and cost-effective maintenance program.

The primary and most essential function of a control system is to provide continual delivery of cathodic protection current to the structure at all times. It is the author’s opinion that the system should have simple functions which can allow the asset owner’s maintenance staff to easily carry out all functional checks without the need for any specific software knowledge.

It is the author’s experience that an optimum control unit for a CP system should consist of the following components:

- Basic and heavy-duty transformer rectifier unit with modular unit design allowing for replacement of components when required without any special programming.

- Interruption facility providing accurate means of performing instant OFF measurements for testing reference electrodes.

- Data logging facility (typically required for large systems only).

- Reliable web-based remote monitoring or standard SCADA connectivity for functional checks only (current or voltage for each circuit). This is required for remotely located installations where such functions cannot be carried out regularly by the asset owner’s maintenance staff.

- All system components must be configured to enable the DC power outputs to operate irrespective of any hardware or software failure of the data logging or remote monitoring equipment.

Materials Selection

Ribbon anode is available from various manufacturers. The key components of ribbon anode are the material substrate, coating composition and the thickness and the uniformity of the Mixed Metal Oxide (MMO) coating. Laboratory testing has recently been carried out of a number of commercially available ribbon anode samples from manufacturers in the US, Italy, China and India. The aim of the testing was to make comparisons between the different ribbon anodes with relation to the material substrate, coating composition, thickness and uniformity of the MMO coating.

The testing revealed that all samples used Titanium grade 1 as substrate. The coating composition for all anodes was deemed suitable for application, however the results show a very large variation between the samples in terms of coating uniformity and coating thickness.

The majority of the samples had a thick coating with a high density of internal cracks. This may have long term effects on the conductivity and life span of the coating, and it is unlikely that these anodes would retain their properties for the 50 year design service life of the anode.

Only one sample, in contrast to the other samples, had an adequate coating thickness for concrete CP application and a uniform and crack-free coating.

The conclusion from this test is that when specifying ribbon anode material, it is essential to ensure that the specified anode has a proven record and a history of performance. Cheaper anode products which have been manufactured in recent years by various suppliers appear to have issues with coating uniformity, and therefore their long-term performance is questionable.

Conclusions

Impressed current cathodic protection in concrete is an ideal technology for the long-term corrosion protection and preservation of infrastructure. A properly designed, installed and monitored CP system can provide long term protection to any structure in a harsh environment with minimal maintenance costs.

Impressed current cathodic protection technology for steel in concrete has now reached maturity and can be utilised as a standard and reliable technique for the long-term corrosion protection of structures suffering from chloride induced corrosion.

With the installation of a large number of CP systems in concrete over the past 35 years in Australia, it is essential that the industry undertakes continual assessments including targeted research programs of various aspects associated with CP systems as deemed necessary with the aim to eliminate errors in design, materials selection, installation, monitoring and maintenance.

The use of heavy duty and reliable power supply units, proper selection and installation of the CP system components, proper CP system design and installation (to eliminate issues such as grout acidification), and the establishment of a cost effective, long term monitoring and maintenance program for CP systems are the key components which will ensure that impressed current cathodic protection systems will continue to be the technology of choice for asset owners in Australia for the long-term protection of their assets.

References

1. A. Cheaitani, et al, Performance of Cathodic Prevention System of Sydney Opera House Underbridge Walk After 10 Years of Operation, NACE 2006 Paper 06342;
2. The European International Standard, Cathodic Protection of Steel in Concrete (2016) ISO 12696:2016;
3. NACE International, Impressed Current Cathodic Protection of Reinforcing Steel in Atmospherically Exposed Concrete Structures. 2007 SP0290-2007 (formerly RP0290);
4. Standards Australia, AS 2832.5 – 2008, Cathodic Protection of Metals, Part 5: Steel in Concrete Structures. 200;
5. Bennett J et al, Cathodic Protection of Concrete Bridges: A Manual of Practice, SHRP –S-372 (1993), page 28.