Review of Cathodic Protection Systems for Concrete Structures in Australia
Lessons Learnt and Future Directions

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SUMMARY:

Impressed current cathodic protection (CP) for reinforced concrete structures is a proven technology which can provide long term corrosion prevention solutions for marine structures. This technology has been employed on a large number of concrete structures in Australia over the past 30 years and it is the technology of choice for many asset owners for the protection of structures suffering from chloride induced corrosion.

While this technology has proven to be very effective for the maintenance of reinforced concrete structures, a review of the performance of many installed systems in Australia has led to the conclusion that there are many areas for improvement that can be implemented to optimise the design of concrete CP systems for new installations and consequently develop systems which can deliver optimum corrosion protection with minimal maintenance and monitoring costs. The areas for improvement include materials selection, design, installation and monitoring of CP systems.

This paper will propose a series of changes to current practices that can be considered for implementation in the design, installation and monitoring of new impressed current cathodic protection systems in concrete.

Keywords: Corrosion, Cathodic, Chloride, Maintenance, Monitoring, Concrete

INTRODUCTION

A large number of impressed current cathode protection (CP) systems in concrete have been installed in Australia during the past 30 years. The majority of these systems have been installed in accordance to international standards, up until the issue of Australian Standard AS2832.5 (1).

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 CP operational criteria.

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 serious implications on the long term performance and maintenance of CP systems.

Based on the results of a number of audits carried out by the author in recent years on various CP systems operating on marine structures in Australia, the majority of the identified problems for these systems 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. For all of the audited CP systems, it was noted that no major reinforcement corrosion issues were identified.

It is the author's opinion that due to the above mentioned issues, partial interruption of cathodic protection current delivery to structures has resulted in high maintenance and rectification costs, however has not reduced the capacity of the CP systems in delivering corrosion protection to the embedded reinforcement.

There is strong evidence (based on the performance data of these systems) that the application of impressed current cathodic protection has provided a long term benefit associated with the transformation of the environment around the steel reinforcement over a period of time and preventing reinforcement corrosion to re-initiate. This has been evident even when the CP current has been interrupted for an extended period of time (such a period could be in excess of 12 months). Similar observations have been concluded in an experimental field study by Christodoulou, C et all (2). Data associated with an ongoing study being currently carried out by the author with relation to the assessment of the long term benefits of impressed current cathodic protection systems in concrete will be incorporated in a separate publication.

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.

What is cathodic protection in concrete

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 the reinforcement becomes a negative pole or cathodic, 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.

PROBLEMS ASSOCIATED WITH CP INSTALLATION

For cathodic protection systems in concrete, the embedded components in the concrete include anodes, anode connections, steel connections, cables, conductor bars and reference electrodes. The components outside the concrete include T/R units, cables, conduits and junction boxes.

It is the author's opinion that most 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. CP system design has been carried out in most cases in such a way that 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.

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

Grout acidification of anodes

Grout acidification has been mainly associated with ribbon anodes which are installed in tidal and splash zones. There is not enough information regarding grout acidification associated with discrete anodes in concrete. The problem is not evident for discrete anodes as acidification may occur within the discrete anode hole.

Based on the author's experience of grout acidification issues with ribbon anodes in numerous structures over the past years, the following observations are noted:

- Grout acidification may not have a short term impact on the performance of a CP system. No direct correlation between grout acidification and initiation of reinforcement corrosion in the areas of grout affected by acidification has been noted even after many years since the initiation of the grout acidification problem. It appears that the CP current delivery from the anode will not be 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 density 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 in many structures for many years. 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 cathodic protection 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 of water exposure are normally specified with Ingress Protection (IP) protection suitable for such exposure. It is the author's experience that regardless of the IP protection for any enclosure, such protection is likely to be seriously compromised during the design life of the CP system when the enclosure is installed in an area of potential water exposure. For junction boxes installed in areas of 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. It is the author's opinion that one year following system commissioning, minimal and less frequent CP system adjustments are normally required to maintain optimum system operation and compliance with current standards.

The author's experience is that regular functional checks of current delivery to a CP system, 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 reducing the capability of the system to provide corrosion protection to the structure;
- Frequent parts replacement, and;
- Excessive costs for monitoring and maintenance.

Workmanship 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 and systematic testing and establishing of continuity between all embedded rebars within the CP zone are some of the key issues which affect CP system operation.

Problems associated with concrete repair

Some CP systems have been installed retroactively to wharf structures under operating conditions. In most of these CP applications, gunite material application has been used. This material has been applied in two layers with the 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 a live load. Extensive testing for this type of apparent defect 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 for various structures has revealed that the grout encapsulating the anode is fully sufficient to pass the CP current to the embedded reinforcement and ensure full 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 anodes are produced by numerous manufacturers around the world. All ribbon anodes have a similar appearance. It is very difficult to make any assessment regarding the suitability of a product based on visual inspection or the information provided 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, and this is because the anode is the primary material delivering the cathodic protection current to 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. These measures are as follows:

- The elimination the use of ribbon anodes 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.

Junction boxes

In terms of reducing maintenance requirements associated with junction boxes, eliminating junction boxes altogether in areas where the junction boxes will be susceptible to water ingress over the design life of the CP system, 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 which are positioned in wet areas reveal the superiority of these approaches in eliminating problems associated with water ingress and damage to the junction boxes.

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. Such 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 current to the structure to ensure protection 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 replacement of components when required without any special programming.
- Interruption facility providing accurate means of performing Instant OFF measurements for the 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 of a number of commercially available ribbon anode samples from manufacturers in the US, Italy, China and India has been carried out recently. 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 30 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

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AUTHOR DETAILS

Atef Cheaitani is the principal and Managing Director of Remedial Technology, a consultancy company specialising in corrosion control for concrete and steel structures. The author's expertise is in the development of various rehabilitation solutions for reinforced concrete structures, including the design of electrochemical systems and the monitoring and maintenance of cathodic protection systems installed in concrete and steel structures.