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Review of Cathodic Protection Systems for Concrete Structures in Australia

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ABSTRACT

Impressed current cathodic protection (CP) for reinforced concrete structures is a proven technology which can provide long term corrosion prevention for marine structures if properly designed and installed. This technology has been applied to 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 susceptible to chloride induced corrosion.

While this technology has proven to be highly effective in providing corrosion protection to embedded steel reinforcement, in some cases, the maintenance and monitoring costs have been relatively high and this is often due to defects during the design and construction stage of the system. The review of performance of many operating CP systems in Australia has led to the conclusion that there are many areas of improvement which can be implemented to optimize the long term performance of impressed current CP systems. The areas of improvement include materials selection, design, installation and monitoring of CP systems.

This paper will provide a case study of a major CP system operating in Australia for 15 years and will propose a series of changes to current practices which can be considered for implementation in the design, installation and monitoring stages of new impressed current cathodic protection systems in concrete.

Key words: Corrosion, Cathodic, Chloride, Maintenance, Monitoring, Concrete

INTRODUCTION

A large number of impressed current CP systems in concrete have been installed in Australia during the past 30 years.

Based on the results from 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 systems were providing adequate

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corrosion protection to the structures with no major deterioration from corrosion issues. The most commonly identified problems were associated with the reliability of control systems and durability issues associated with various CP system components. This paper will present the results of an audit performed on a major cathodic protection system in Australia which has been operating for 15 years, and also present various recommendations and suggestions related to the design of new CP systems for concrete structures.

CASE STUDY - PORT OF BRISBANE WHARVES 4 & 5

An impressed current cathodic protection (ICCP) system was installed and commissioned on selected reinforced concrete elements of Port of Brisbane Wharves 4 and 5 in 1999.[1] The CP system was installed in conjunction with major repair work to key structural elements of the wharves including the abutment, the front and rear crane beams, the relieving slab and the fenders.

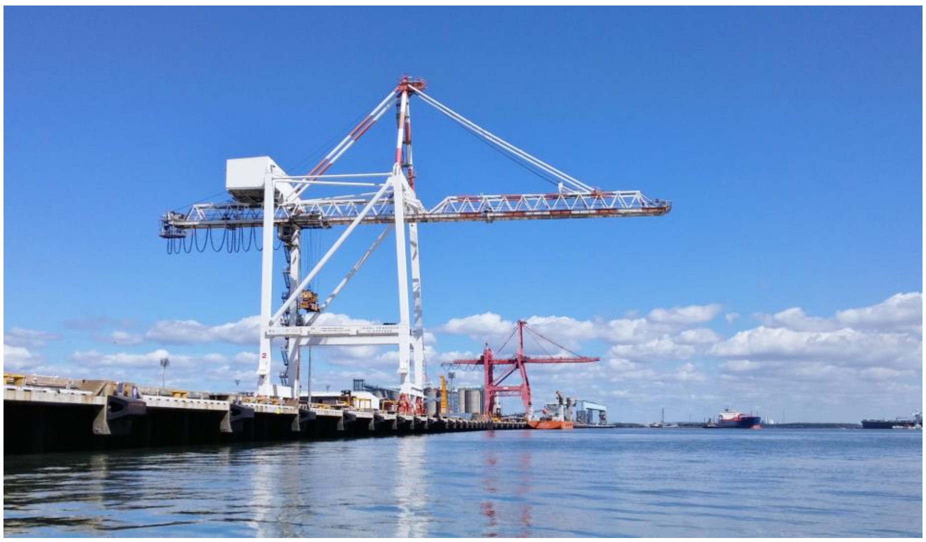

Figure 1: Port of Brisbane Wharves 4 & 5

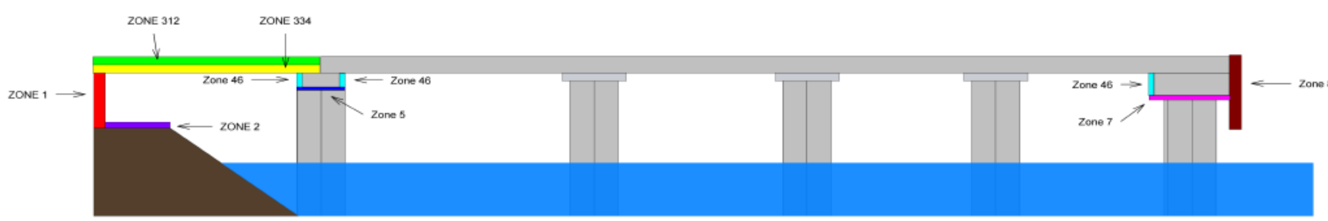

Figure 2: Cathodic Protection System Zoning

After 15 years of system operation and following flooding of the Brisbane river, a comprehensive audit of the wharves was commissioned by Port of Brisbane. The audit was to assess the current status of the structures, the CP equipment and to assess the need for any rectification work in order to maintain system operation and extend the service life of the wharves for an additional 30 years.

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The audit included a detailed review of CP system performance, an inspection of the structures and an inspection of the cathodic protection system components such as conduits, junction boxes and control units.

A brief summary of the audit results is as follows:

- The protection criteria had been achieved for nearly all embedded reference electrodes based on the current applicable Australian Standard AS 2832.5 - 2008.[2]

- The areas protected by CP were free from spalling and reinforcement corrosion, with the exception of a very small localized area of approximately 6 m^2.

- In the splash and tidal zone areas, and where the ribbon anodes were installed in slots cuts in the concrete, there was evidence of grout acidification and missing grout in various locations.

- For a number of the junction boxes and control units located at the abutment wall which is subject to water exposure at high tide and river flooding, various degrees of water damage to components of the control units and the junction boxes was noted. It appears that past re-sealing of these enclosures was undertaken as part of the monitoring and maintenance of the CP system and this work was sufficient to maintain continuity of system operation at all times.

On the basis of the audit results, a rectification program was initiated by Port of Brisbane. The approach had a pro-active and long-term view to permanently deal with the problem of water ingress into CP enclosures, in order to eliminate any interruption of CP current delivery to the wharves as a result of damaged components. The initial part of the rectification program was to replace all junction boxes located in areas susceptible to water exposure and re-locate control units from their current location under the wharves to new locations above the wharves and away from any water exposure. The secondary part of the rectification program dealt with the remaining aspects of work, such as grout acidification repair on the concrete elements. The initial part of the rectification program was completed in August 2015. The secondary work is undertaken as part of general maintenance work of Port of Brisbane's assets.

In order to complete the initial work in the most cost effective way, an assessment of CP system performance data over the past 15 years was performed and a new design was prepared on the basis of combining various circuits of the CP system without affecting the level of CP system control and long term system performance.

Assessment of the Structure

Grout Defects

- Grout acidification has mainly been associated with the ribbon anodes which were installed in the tidal and splash zones. It appears that the grout acidification has had no impact on the performance of the CP system. There was no evidence during our audit for any correlation between grout acidification and initiation of reinforcement corrosion in the areas of grout affected by acidification, even after many years since the initiation of the grout acidification problem. It appears that the CP current delivery from the ribbon anodes was not significantly impacted by the grout affected by acidification.

- There was no evidence of direct correlation between the initiation of grout acidification and the 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

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grout acidification. Possibly, the direct exposure of the ribbon anode to water was the primary cause of initiation of the acidification process.

- In the tidal zone area (the abutment slab for this installation), in various locations some loss of grout material from around the ribbon anode locations was observed. In these circumstances, the ribbon anode has been immersed for a certain period of time every day in salt water subject to tidal movements. The ribbon anode has been operational while immersed in water, and based on our audit, no concrete deterioration was observed in the tidal and splash zones as a result of grout acidification, or where the anode is fully exposed without grout. It appears that partial delivery of 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.

- Missing grout material was identified in various isolated locations. It appears that the missing grout problem was typically in the perpendicular slot cut areas with 30 mm depth x 6 mm width.

Concrete Condition

- For the entire area protected by CP application at Wharves 4 & 5, only one area of approximately 6 m^2 (out of an approximate total area of repair of 5000 m^2) was delaminated. The primary cause of this localized delamination was related to the CP system not operating in this subzone due to a localized short circuit between the anode and steel.

- The CP system had been installed to Wharves 4 & 5 under wharf operating conditions. For large areas on the CP protected structure, gunite material application had been adopted during installation. This material had been applied in two layers with the ribbon anode installed between the layers of gunite material.

- During delamination testing, some areas (specifically in the front and rear crane beams) produced a ‘hollow’ sound and were detected as potential delaminated areas. A detailed inspection at these suspected areas and testing at various breakout locations revealed that the gunite material encapsulating the anode was fully sufficient to pass the CP current on to the embedded steel reinforcement. The suspected delamination proved not to be associated with any corrosion of the steel reinforcement.

Inspection of Junction Boxes and Control Unit Enclosures

Due to space restrictions on the wharf deck, the system’s control units and all junction boxes were originally installed under the wharves in IP67 rated enclosures (totally protect against dust and no harmful effect of water dip in certain levels of pressure and length of time – 1 m depth water for 30 minutes in accordance to IEC60529). At the time of system installation, it was considered that IP67 enclosures (which were assumed to provide protection against immersion between 15 cm and 1 m) would be sufficient to provide protection to all of the components within the enclosures against potential moderate water exposure at high tide.

The inspection was carried out to the 13 control units located in separate enclosures along the abutment wall below the wharves. There are also 96 junction boxes located at the abutment wall (which are subject to water exposure) and 96 junction boxes located at the front crane beam.

The audit results revealed that the 96 junction boxes located at the front crane beam and away from the water were in excellent condition.

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Approximately 50% of the control units and 50% of the junction boxes located at the abutment wall, in an area which is subject to water exposure, had various levels of water damage inside to terminals and electronics.

A detailed inspection of the failed junction boxes revealed that the primary causes of defects were:

- Movement in the structure causing physical damage to the junction boxes in the form of cracking to the IP67 enclosures and allowing water ingress into the junction boxes;
- Failure of the rubber seal cover of the junction boxes; and
- Failure of the sealant applied around the conduit entries.

For the control units, the primary cause of water ingress was the defective rubber seal of the cabinet doors, and in some cases, ingress of water through the conduits terminated at the control units.

It appears that since system commissioning in 1999, various measures such as periodic re-sealing of junction boxes and control units was undertaken to prevent water ingress into the control units and junction boxes. These measures allowed the system to continue to be functional, however, water ingress due to the very harsh marine environment and high humidity exposure could not be fully prevented and has impacted on the long-term performance of the electronics and has resulted in a higher rate of failure of electronic components and increased maintenance costs.

Overall, the original control system installed for the structure performed highly satisfactorily since commissioning. The only issue with this system was the location of the control units underneath the wharf which made them susceptible to water and moisture exposure and increased the failure rate of some system components. Nonetheless, the system provided very accurate readings, especially for instant OFF measurements, and over the years the accurate system measurements consequently led to accurate adjustment of the system and optimum protection of the structure.

Rectification Work

The scope of the rectification work was to replace all 96 junction boxes located at the abutment wall and to relocate the transformer/rectifier (T/R) units to new locations above the wharves.

In order to develop a sound and workable methodology for the rectification work of the junction boxes, a trial application was carried out for a small number of junction boxes. The aim of the trial application was to assess the exact status of the cabling and junction boxes and to develop the optimum methodology for the rectification work.

The new system design included an overall reduction of number of circuits from 14 to 8 circuits in each typical section, and the reduction of the number of T/R units from a total number of 13 localized control units under the wharves, to 6 control units located above the wharves. The combination of system zoning was based on combining smaller circuits with the same exposure conditions and CP current requirements as per the original design. Cable design and voltage drop calculations were performed for all cables between the structure and the new location of the T/R unit. Different sized cables from 4 mm to 16 mm were used between the junction boxes at the wharves and the new locations of the control units in order to ensure proper current delivery to all system zones. The new design resulted in a reduction in the number of zones (circuits) from 172 circuits to 48 circuits.

Audit Conclusions

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1. The operating CP system has provided excellent corrosion protection to Wharves 4 & 5 since its commissioning. This system was applied in 1999 to large repaired areas (5,000 m^2) and to large areas of good concrete, albeit with a high level of chloride contamination. Across all of these areas, cathodic protection application was able to fully stop the corrosion of reinforcement and ensure the serviceability of the structures.

2. In some of the damaged junction boxes, the labelling of cables was substantially damaged and prevented cable identification during the repair work. The original CP system cabling was designed in such a way that for each zone, in addition to labelling, all cables are identifiable by size and color. This has made the entire cable rectification process simple, accurate and fast. The use of individual single insulated cables with different colors (to identify different circuits between the junction boxes and T/R units) instead of multicore cables proved to be vital in this case for the rectification process.

3. The original system was designed in such a way that a reference electrode was installed for every subzone of the system and also the current delivery to every subzone could be verified through current measurement of the dedicated cable terminated at the control unit. This system design was extremely valuable during the repair process as it allowed full verification of the operation of every circuit of the CP system during the rectification process.

4. The use of ribbon anode for this structure would even today be considered as the optimum solution due to the geometry of the elements protected by CP application. Due to knowledge about acidification problems today, which was not available at the time of the initial design, an alternative detail for anode encapsulation would be recommended. The main changes are alternative slot details using different grout for encapsulation (a high pH grout to slow down the potential acidification process) and encapsulating the slot anodes with an additional layer of special cementitious waterproofing material to eliminate ingress of water to the anode location.

5. The 30 mm x 6 mm slot anode detail is an adequate detail for cathodic protection design consideration, however it appears that encapsulating the anode with grout and ensuring adequate cover to the anode may not be easily achievable on site unless a systematic methodology and strict quality controls are in place. Possibly a 20 mm x 30 mm slot cut for ribbon anode application followed by a cementitious overlay would be a more appropriate detail for anode encapsulation.

6. In theory, designing CP systems with small circuits provides a higher level of control of the cathodic protection current. However, this requires more cabling, more reference electrodes and a larger number of power supply units. The conclusion from our audit based on the original system data and the current data of the system following combining various zones (with the same exposure and cathodic protection corrosion current requirements) indicate that larger cathodic protection zones offer the same level of protection. This finding is important as a design consideration for new systems. It has a significant impact on the cost of CP installation by substantially reducing the cost of cabling, T/R units, reference electrodes and junction boxes. Large electrical zones (6 Amps to 10 Amps) can provide the required protection providing other considerations such as concrete resistivity, CP current requirements, chloride level…etc. and cabling design are taken into account during the design process.

7. In theory, it is assumed that the initial current in a CP system will be substantially reduced over the life of the system as the steel is polarized and therefore a lower CP current could achieve the same level of protection during the life of the structure. Based on 15 years of data of the CP system at wharves 4 and 5, it appears that this was not the case for these structures. There was minimal reduction of the required CP current to achieve protection based on current applicable standards during the life of the system. The initial global impressed current at commissioning was 100.9 Amps compared to 90.2 Amps after 15 years of system operation. The relatively minor

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reduction of current requirement for this wharf after 15 years of system operation is a clear indication that impressed current CP technology is the only technology that can provided the required long term corrosion protection for structures located in harsh marine environment.

8. The installation of junction boxes and control units in areas which may be susceptible to water exposure must not be considered for new installations. The potential initial cost of additional cabling to allow for the installation of the control units away from areas of water exposure is negligible compared to the cost of continuous maintenance of the control units and potential full replacement of the junction boxes due to damage. Eliminating junction boxes altogether from 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.

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 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 110 mA/m^2 of anode surface.

- Use of special CP grout which is specially formulated to minimize 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

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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.

CONCLUSIONS

Impressed current cathodic protection in concrete is a proven technology for the long term corrosion protection and preservation of infrastructure. A properly designed, installed and monitored CP system can provide long term corrosion protection to any structure situated in a harsh marine environment.

The level of cathodic protection current required for the corrosion protection of the subject wharves to meet the requirements of the Australian Standard AS 2832.5-2008, or any international standards such as the NACE Standard SP 2290-2007[3] and European Standard ISO 12696:2012,[4] did not substantially decrease after 15 years of system operation. The required level of cathodic protection current, which was on average in excess of 10 mA/m² of steel surface area at commissioning, clearly indicates that any sacrificial based anode system would not under any circumstances have the capacity to deliver this level of cathodic protection current and hence provide the required corrosion protection of the wharves

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in accordance to the current Australian or international standards for cathodic protection of steel in concrete.

The use of reliable power supply units, proper selection and installation of CP system components, proper CP system design and installation, and the establishment of an efficient, simple and reliable long term monitoring and maintenance program for CP systems are the key components needed to ensure that impressed current cathodic protection will continue to be the technology of choice for asset owners for the long term protection of their assets.

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