MANAGEMENT OF CATHODIC PROTECTION SYSTEMS IN MARINE ENVIRONMENTS

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SUMMARY: Impressed current cathodic protection (ICCP) for reinforced concrete structures is a proven technology which can provide long term corrosion prevention solutions for marine structures. The three main issues associated with the long term performance and low cost maintenance of a CP system are the adequacy of the initial design and installation of the CP system, the durability of CP components and the maintenance and monitoring of the system.

This paper will present various electrochemical technologies used in Australia for the corrosion protection of chloride contaminated structures and will highlight various key design and installation issues which are essential for the optimum long term performance of cathodic protection systems. In addition, the paper will present a Cathodic Protection Management System (CPMS) which offers a reliable, cost effective and efficient tool for the long term maintenance and monitoring of large or multiple CP installations.

The Cathodic Protection Management System (CPMS) combines the development of a database for the management of CP systems, with a comprehensive program for system maintenance. This program incorporates monitoring, routine inspections of the structures, defect rectification of CP components and T/R units, rectification of all defects of the structures and provision of updated status reports to owners for maintenance planning.

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

1. INTRODUCTION

Over the past 25 years, impressed current cathodic protection systems have been used extensively in Australia for the corrosion protection of marine structures suffering from chloride induced corrosion.

Chloride induced corrosion is the most serious cause of deterioration in reinforced concrete structures. The presence of chloride in concrete does not directly affect the concrete, but rather allows corrosion of the steel reinforcement to occur. The chloride in the corrosion reaction on the steel surface is not consumed, thus the reaction will continue until all of the raw material of the corrosion process, namely steel and oxygen, are consumed.

The following methods have been applied in Australia for the corrosion protection of chloride contaminated structures:

1. Full or partial rebuild of the structure;
2. Removal of all concrete where critically high levels of chloride have penetrated;
3. Cathodic protection;
4. Galvanic protection; and
5. Chloride extraction.

This paper will present the key aspects associated with these technologies as well as the author’s opinion in relation to their effectiveness for the corrosion protection of steel reinforcement in chloride contaminated environments.

2. CORROSION CONTROL METHODS FOR CHLORIDE CONTAMINATED STRUCTURES

2.1 Full Rebuild or Chloride Contaminated Concrete Removal

There is no doubt that a full or partial rebuild of the structure or the removal of all concrete with high levels of chlorides provide the optimum long term rehabilitation solution with low monitoring and maintenance costs. However in practice, in nearly all cases this solution cannot be applied due to cost and structural considerations.

2.2 Cathodic Protection

Cathodic protection (CP) is the oldest and most proven electrochemical technology applied to reinforced concrete structures. Cathodic protection 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 removes the chloride ions away from the steel towards the anode.

There are various types of impressed current anodes applied to atmospherically exposed reinforced concrete. In Australia, the most commonly used types of anodes are Mixed Metal Oxide (MMO) mesh or ribbon anodes in a cementitious overlay or in grout filled chases and MMO discrete anodes embedded in drilled holes in the concrete.

For impressed current CP systems, it is essential that the system is regularly monitored as a part of the maintenance program of the asset.

Impressed current cathodic protection technology has gained very rapid acceptance in Australia over the past 25 years. As a result, many structures suffering from chloride induced corrosion are protected by cathodic protection systems.

Key features of this technology are:

- Environmentally friendly: major reduction of concrete breakout.
- Maintenance: regular monitoring is essential to ensure the optimum operation of the system.
- Long term global/local protection: provides effective treatment for the entire area of application. Areas with high levels of corrosion can be targeted with localised CP application.
- Proven technology: long history and an excellent track record.

Application:

- Chloride contaminated structures in marine environments and in particular tidal, splash and atmospheric zones (wharves, dolphins, bridges… etc).
- Structures with high corrosion activities or/and constant exposure to chloride ingress.
- Structures where long term reliable and effective corrosion protection is required.

The applicable standard in Australia for impressed current CP systems in concrete is AS 2832.5-2008 – Cathodic protection of metals Part 5: Steel in concrete structures [1].

2.3 Galvanic Protection

Galvanic cathodic protection is currently an area of substantial growth. It is becoming increasingly attractive because of its simplicity and low monitoring and maintenance requirements. The anode which is normally made from metal such as zinc, is connected to the reinforcing steel and the potential difference between the zinc and the steel causes a small protection current to flow from the zinc to the steel.

Galvanic anodes may broadly be divided into surface-applied systems and embedded discrete systems. The surface applied systems achieve relatively good current distribution but poor adhesion in comparison with the embedded discrete systems.

Galvanic anodes in concrete are usually supplied with proprietary backfill which provides space for the products of anodic dissolution. Most of the recent innovation and research in galvanic anode technology has been associated with the backfill material.

The hybrid anode system which is a relatively recent development differs from the purely galvanic systems described above. The hybrid treatment consists of a temporary impressed current followed by permanent galvanic protection. The principle of the system is that during the initial impressed current phase, active pits are realkalised stopping active corrosion and returning the steel to a passive state. Following the application of the impressed current phase for a predetermined period, the passivity of the steel is maintained by the sacrificial anode system.

Key features of this technology are:

- Low monitoring and maintenance requirements.
- For buried/submerged applications, galvanic anode systems have an excellent performance track record.
- Under suitable conditions and generally when the corrosion activity is low, the galvanic systems for concrete atmospheric applications may provide some level of protection against reinforcement corrosion.
- Performance data from site applications suggests that it is unlikely for galvanic or hybrid systems to achieve the cathodic protection criteria in accordance with current standards for heavily chloride contaminated marine structures especially for areas of high corrosion activity and with direct exposure to tidal and splash zones.

Application:

- In structures where a permanent power supply required for an impressed current system is unavailable.
- In conjunction with patch repair to reduce the effect of incipient anode.
- In structures with only light chloride contamination and where low cathodic protection current density is sufficient to achieve an adequate level of protection.

2.4 Chloride Extraction

Electrochemical desalination or chloride extraction involves a technique whereby a current is passed through the concrete to the reinforcement by means of an externally applied anode which is temporarily attached to the concrete surface. A paste of sprayed cellulous fibre with a conductive solution is normally used as the electrolyte covering the concrete surface.

The duration of the treatment is typically between 4 to 10 weeks. A variety of electrolytes can be used. During treatment, chlorides migrate out of the concrete towards the external anode and are collected in the electrolyte reservoir. At the same time, hydroxyl ions are produced at the surface of reinforcement re-passivating the steel reinforcement.

This technique has not been used extensively in Australia due to the fact that most of the problems associated with chloride induced corrosion are in tidal and splash zones. The application of this system is not appropriate under these conditions as ingress of chloride cannot be prevented in these areas after the completion of the chloride extraction process. For structures away from tidal and splash zones, prevention of new chloride ingress after the chloride extraction process requires that the concrete is protected by an anti-chloride protective coating.

Key features of this technology are:

- Environmentally friendly: major reduction of concrete breakout.
- Low maintenance: no requirements for a permanent monitoring system.

- Long term global protection: provides effective treatment for the entire area of application.
- Proven technology: long history and an excellent track record.

Application:

- Chloride contaminated structures that are not subject to constant exposure to salt contamination such as tidal and splash zones in marine environments.

The applicable standards for chloride extraction treatments for reinforced concrete are CEN / TS 14038 -1 [2] and NACE SP0107-2007 [3].

3. CATHODIC PROTECTION DESIGN

3.1 Electrochemical Testing

One of the key aspects for the successful application of a CP system is to undertake a condition assessment of the structure and ensure the suitability of CP application for the structure. Some partial failures in CP systems are due to unsuitability of CP application, for example, where there is lack of continuity of reinforcement or the concrete resistivity is very high.

The relevant tests include cover to reinforcement, delamination testing, chloride level concentration profile of the concrete, concrete resistivity, half-cell potential mapping and reinforcement continuity. The condition assessment is essential for determining the zoning of the CP system and individual areas where there is significant change in the environment and the steel density. In Australia, the majority of the CP systems are installed in marine environments. System zoning is determined based on tidal levels, potential mapping testing, resistivity measurement and chloride profiles.

Another key issue in CP system design is to ensure that it is engineered in such a way that simple verification of the current delivery for each element of the structure can be achieved as part of routine system monitoring. A combination of cabling design and the selection of reference electrode locations can allow for the verification of current delivery to each element of the structure during routine site visits.

3.2 Current Density

The selection of a suitable current density output is one of the most critical aspects of CP system design. The application of a fixed current density such as 10mA or 20mA/m^2 of steel surface may not be sufficient to provide adequate protection under all circumstances. The current density requirement is dependent on the level of steel corrosion and the environment surrounding the steel. The current density requirement can range from less than 2 mA per m^2 of reinforcement for alkaline concrete with high concrete cover and low corrosion activity, to in excess of 35 mA per m^2 of wet, heavily chloride contaminated poor quality concrete with low to medium concrete cover.

3.3 Current Distribution

The optimum current distribution is determined based on the level of reinforcement corrosion, concrete resistivity and rebar arrangement. The potential mapping test combined with concrete resistivity testing are essential for the proper understanding of the current distribution requirement. The highest level of current should be injected in the areas of active corrosion. In areas with a large variation of concrete resistivity, discrete anodes can provide higher flexibility for targeted current injection as opposed to surface mounted anodes such as ribbon or mesh anodes. There are several significant issues which can impact the selection of the current density and current distribution. In most cases, taking into account all of these issues may not be a straight forward exercise and may require the special expertise and experience of a design engineer. In order to eliminate the risk of over or under design, it is highly recommended that a trial be installed to verify the design assumptions and to confirm that the system will provide the optimum corrosion protection.

3.4 Cathodic Protection Component Selection

The primary components of CP systems are the anodes, the grout surrounding the anodes, conductor bars, anode and steel connections, reference electrodes, junction boxes, cabling, conduits and control systems.

Based on the author's experience, most of the problems with Australian CP systems are associated with the durability of junction boxes when installed in wet areas, acidification of grout for anodes installed in wet areas and the long term reliability of the control systems.

For the grout acidification issues, specific design of the CP system is required for all areas which may be subject to grout acidification with relation to anode current density, anode embedment details, grout selection and special coating application.

For junction boxes, eliminating junction boxes altogether in the design process or alternatively, permanently sealing the junction boxes should be considered in cases where the junction boxes are to be installed in wet areas.

For the control systems, various types of control systems have been installed in Australia over the past 25 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 advanced levels of alarm functionality. It is the author's opinion that while it may be desirable to install very advanced and sophisticated control systems, generally, such systems can be complex to maintain and some require highly skilled personnel with specialised software knowledge to operate their functions.

It is the primary and most crucial function of a control system to provide continual passage of current delivery to ensure the protection of the structure at all times. For this particular reason, simple, heavy duty and more robust systems must be the primary priorities for any control system selection.

With recent advancements in commercial heavy duty data logging equipment and reliable web-based remote monitoring, it is now viable to incorporate a data logging and remote monitoring facility with a heavy duty and robust manual transformer rectifier unit. Such a combined system can be designed so that each system component can be configured to enable the DC power outputs to operate irrespective of any hardware or software failure of the data logging equipment or the remote monitoring equipment. A key selection criterion must be that all system components are of a heavy duty industrial type and suitable for operation in aggressive humid environments and with a proven record of reliability and long term performance.

It is the author's opinion that collecting large amounts of cathodic protection data and having remote functionality for testing, while seemingly desirable, it is not essential for the long term monitoring of the CP system and corrosion protection of the structure. The complexity of maintaining such systems (which typically operate on proprietary software) is not justified in comparison to the benefits of using simple, reliable manual systems with basic functionality for data logging, monitoring and alarm functions.

For this reason, a simple monitoring system that can ensure cathodic protection current is delivered to each zone of the CP system and that current delivery is within the range that will provide protection to the embedded reinforcement is the optimum requirement. In order to achieve the above aim, only relevant data should be monitored and stored. This data can be limited to the current for each zone of the CP system. Any failure of current delivery to any zone of the CP system should also be detected through the alarm system.

4. CATHODIC PROTECTION INSTALLATION

The correct installation of a CP system is essential for long term operation over the system's design life. One of the most critical issues is verification of 100% continuity in the embedded reinforcement. A high level of attention to detail must be given to the embedment of anodes and the proper selection of locations for reference electrodes (subject to specification requirements). Another key aspect for ensuring correct CP system installation is carrying out progressive energising of the system during the installation process. This will allow defects to be identified progressively and then rectified during the construction process.

5. CATHODIC PROTECTION SYSTEM MAINTENANCE AND MONITORING

It is the role of the consultant, as part of recommending the installation of a CP system, to ensure that the asset owner is fully aware of the importance of ongoing monitoring and maintenance of the CP system and structure. This process should ideally be established at the commissioning stage and should be organised in a systematic and efficient way. A Cathodic Protection Management System (CPMS) has recently been implemented to multiple CP installations operated in NSW for the Road and Maritime Services and for the Department of Crown Lands.

5.1 Cathodic Protection Management System (CPMS)

The primary aims of a CPMS is:

1. Provide a permanent online database of CP systems incorporating all key CP data which is required for long term CP system operation and the maintenance of the structures.
2. Ensure continuous delivery of CP current to all structures at all times.
3. Provide a platform for owners to verify the status of the CP systems allowing for the systematic planning of maintenance work to the structures.

A Cathodic Protection Management System (CPMS) has the following main components:

i. General global information
ii. Key system data
iii. Maintenance and monitoring data
iv. Reporting system

A typical layout for a CPMS for multiple structures is shown below:

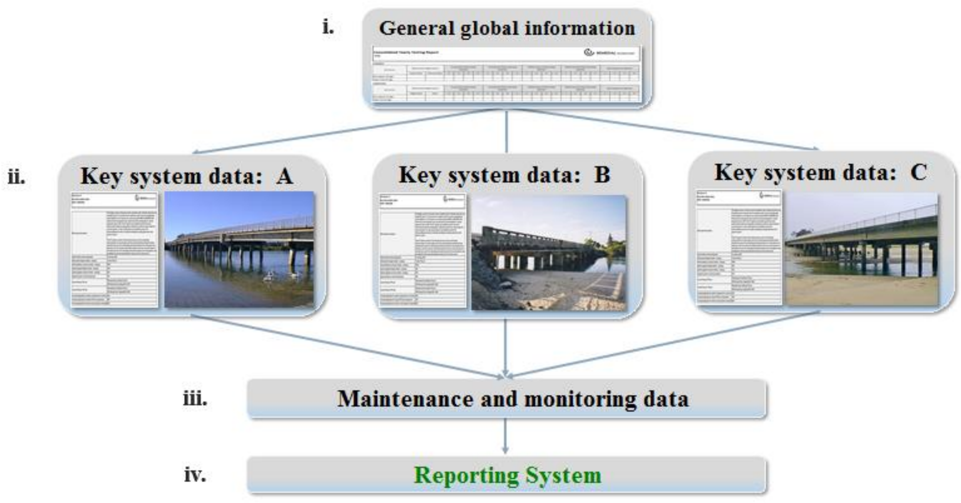

Figure 1: The example above is for three separate structures with CP installations.

5.2 CPMS Components

i. General global information – This section includes common information applicable for all structures and can be updated when necessary. Typical content in this section includes: monitoring and inspection guidelines based on all applicable Australian Standards, a yearly maintenance and monitoring program for all structures, generic Test Method Statements (TMS) and generic Work Method Statements (WMS) for minor work, records of the repair of T/R units and structures and all general forms related to the inspection and the monitoring of the structures.

ii. Key system data – This section includes the original specification, drawings, the operation manual for each system, the system commissioning report, all past monitoring reports for the system, key information data for each system which includes a general CP system description, warranty information, address and contact details of manufacturer of control system…etc.

iii. Maintenance and monitoring data – Includes all yearly data associated with functional checks, cathodic protection performance reports and the yearly inspection reports of the systems.

iv. Reporting system – This includes a summary of all yearly planned and completed activities associated with the systems. This section allows the owners of the structures to verify online all planned and completed activities and also to access all information related to the recommended maintenance of the structures.

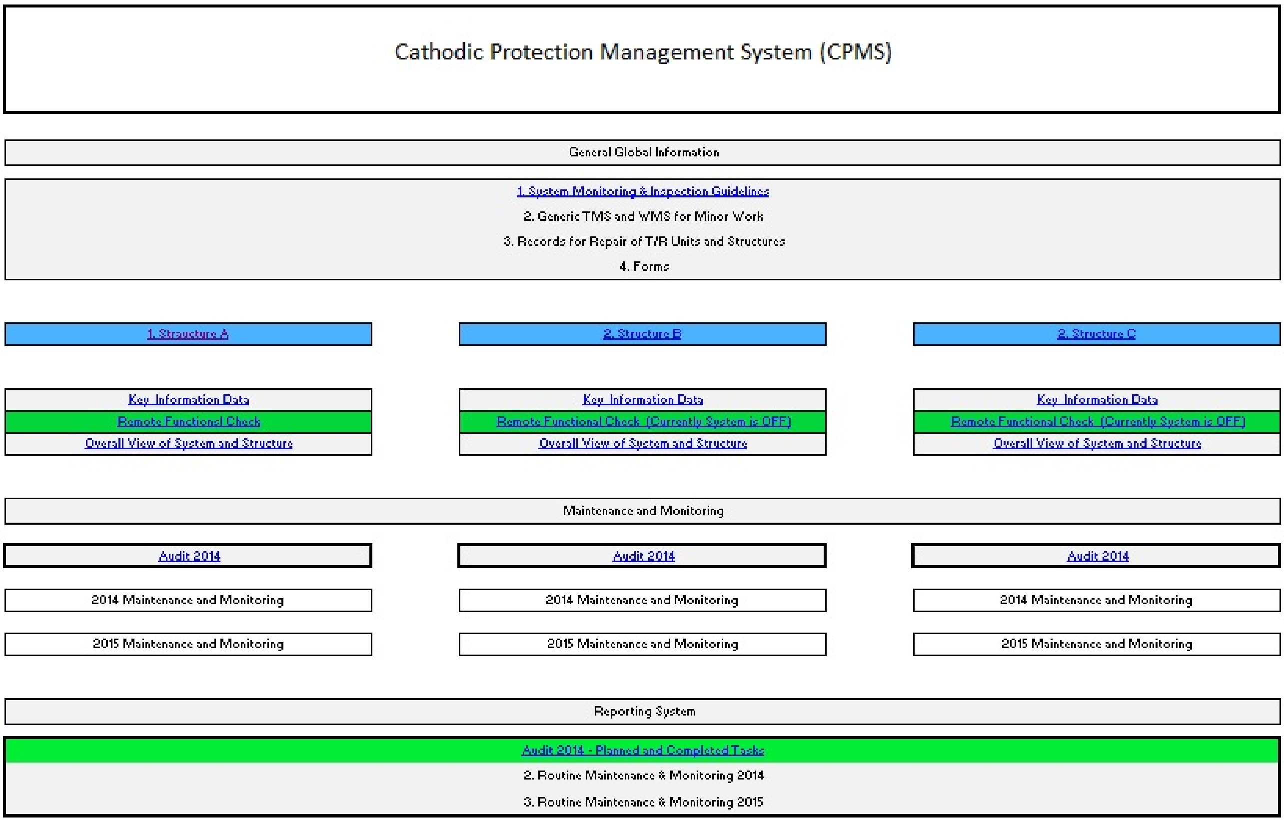

Figure 2: Example of the structure of a cathodic protection management system.

5.3 Planning for Longevity of an Asset

In order to achieve the optimal long term performance of an asset, maintenance planning must be simple, reliable and planned over the asset's entire life span. To achieve this, owners must organise and consolidate their system information for the purpose of planning maintenance requirements, and be able to adequately pass on this responsibility to their successors who will continue with this responsibility.

The application of cathodic protection systems to structures has a significant initial cost, and some ongoing costs associated with monitoring and maintenance work. When system information is properly maintained, maintenance issues and problems are easily identifiable and rectification work (where required) can be carried out in a timely manner. This keeps maintenance costs to a minimum over the life of the structure and this is an important consideration for all asset owners.

5.4 Audits

An initial major site audit of the CP system and the structure by an experienced cathodic protection engineer is a key component of a CPMS. Based on the author's experience in auditing CP systems, it is frequently revealed that there are some non-performance issues with the cathodic protection system of the structure. Some issues are minor while others are serious and related to the protection systems, with some problems having been consistently overlooked for years.

5.5 Decision Making

One of the key barriers to the efficient running of a CP system or multiple systems, is the large volume of reports, operation manuals, technical specifications & drawings and other documentation which is normally kept on file. It is often the case that this documentation is unorganised, and contains a lot of duplicate and irrelevant information. This state can potentially clutter and slow down the decision making process for owners. In the worse cases, it may lead to necessary maintenance actions being delayed or completely overlooked.

The objective of a CPMS is to consolidate online all CP system data which is essential for system monitoring and maintenance, and to eliminate all standard reporting. Any inspection reports, functional checks and monitoring reports are uploaded into the CPMS after completion and are immediately available to asset owners. This allows asset owners to verify the operational status of the systems at any time, and facilitates clear and achievable long term maintenance planning.

6. CONCLUSIONS

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. However, all professionals in the field of cathodic protection must ensure that the optimum design, material selection, installation and monitoring are carried out properly and professionally.

Various aspects of cathodic protection of steel in concrete structures are detailed in AS 2832.5. The International and Australian Standards for cathodic protection in concrete are well established and are now available to assist owners, consulting engineers and contractors to correctly design, install, test, commission, monitor and maintain impressed current cathodic protection systems.

The proper design of CP systems and the selection of heavy duty, reliable components & control systems combined with the establishment of an efficient maintenance and monitoring program for the structure will ensure that the maintenance of the CP system becomes a routine aspect of the overall maintenance of the asset and that permanent and cost effective corrosion protection is achieved for the structure.

7. REFERENCES

1. AS 2832.5-2008 – Cathodic protection of metals Part 5: Steel in concrete structures.
2. Electrochemical realkalisation and chloride extraction treatments for reinforced concrete, CEN / TS 14038 -1.
3. Standard Practice: Electrochemical realkalisation and chloride extraction treatments for reinforced concrete, NACE SP0107-2007.

8. AUTHOR DETAILS

A. Cheaitani is the Founder and Managing Director of Remedial Technology Pty Ltd, an independent consultancy firm in the area of corrosion control for concrete structures. The author’s expertise includes condition assessments and the development of rehabilitation solutions for concrete structures, including cathodic protection (CP) system design and maintenance systems for concrete and steel structures. Atef has substantial experience in the application of advanced concrete repair technologies and he pioneered the introduction of cathodic prevention technology to Australia in 1995, to China in 2004 and to India in 2013.