

New developments for corrosion protection of concrete structures in Australia

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Abstract. The corrosion protection, repair and maintenance of reinforced concrete structures located along the coast of Australia has been a challenging task for engineers and asset owners over the past thirty years. Most of these structures are bridges and wharves which are situated in marine environments and are subject to tidal exposure. These environmental conditions create challenges in planning repair work, especially if electrochemical systems such as cathodic protection are installed for corrosion protection of these assets. While impressed current cathodic protection (ICCP) is a proven technology which can provide long-term corrosion prevention solutions for marine structures, this technology has been viewed by many asset owners as overly complex and expensive. There is the perception that ICCP systems require costly permanent monitoring programs and have high maintenance costs. These perceptions have been supported by the frequent failure of power supply units, and in some cases, widespread defects associated with ICCP systems such as grout acidification in concrete elements situated in tidal zones. The perception about the complexity of ICCP technology has led to the selection of less effective galvanic-based systems for the protection of assets, and systems which require no monitoring and have low maintenance requirements. This paper will present information on the new developments which have emerged from long-term experience and research work related to the simplification in the design, installation and improved monitoring of ICCP systems.

1. Introduction

Impressed current cathodic protection (ICCP) for reinforced concrete structures has been employed on a large number of concrete structures in Australia over the past thirty years, and up until recently, ICCP has been the technology of choice by asset owners for the corrosion protection of chloride contaminated structures.

In spite of the proven long-term benefits of ICCP technology, in recent years some assets owners have been inclined to select galvanic-based anode systems for the corrosion protection of their assets. One of the primary reasons has been the perception that galvanic based anode systems offer the same level of corrosion protection to structures as ICCP systems, while eliminating the requirements for ongoing monitoring and maintenance work.

This paper will present the theory of ICCP and galvanic anode systems, highlight the advantages and disadvantages of each approach and present various information about recent new developments and improvements related to the simplification in the design, installation and monitoring of ICCP systems.

2. Corrosion Protection Systems

2.1 What is cathodic protection?

When steel corrodes in concrete, the electrochemical 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 conventional batteries) which 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'.

When steel reinforcement begins to corrode in concrete, a small area becomes the positive pole (anode) and another much larger area becomes the negative pole (cathode). The corrosion current flows out of the steel at the anode (the corroding part), passes through the concrete and to 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 oxide.

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.

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In concrete, the corrosion circuit is buried in the structure and the electrical current running through the concrete cannot easily be disconnected. Cathodic protection technology is based on stopping the current from running through the concrete by providing a new current from an external source via an external anode in contact with 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 reinforcement becomes the negative pole or cathode, and hence the name ‘cathodic protection’. For concrete structures, there are two types of cathodic protection systems; impressed current cathodic protection (ICCP) and galvanic anode systems.

2.1.1 ICCP systems

Impressed Current Cathodic Protection (ICCP) technology is a well-established technology for the corrosion protection of concrete structures. All aspects related to the design, installation, monitoring and protection criteria for ICCP systems are documented in global standards such as the NACE Standard SP 2290-2007 (1), the International Standard ISO 12696:2012 (2) and the Australian Standard AS 2832.5-2008 (3).

With large numbers of ICCP systems installed in Australia over the past thirty years, there have been some issues associated with ICCP system design, installation and durability. These issues are mostly related to; complexity and poor reliability of power supply units and control systems; poor design, resulting in durability issues associated with CP system components such as junction boxes; inadequacy of grout properly encapsulating the anodes and shortfalls in establishing simple maintenance and monitoring programs for these systems.

These issues are often related to incompetent design, a lack of understanding by CP designers of the criteria for selecting control and monitoring systems, construction quality issues due to poor workmanship, and a lack of priority for the long-term durability requirements of system components especially when constructed in harsh and aggressive marine environments (4). In spite of these issues, it is generally accepted that a well designed and monitored ICCP system can deliver optimum corrosion protection to a concrete structure and meet the protection criteria in accordance with the applicable standards.

2.1.2 Galvanic systems

Galvanic anode systems are currently an area of substantial growth. This technology is becoming increasingly attractive because of its simplicity and low monitoring and maintenance requirements. The anode which is normally made from a 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 in concrete are usually supplied with a 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.

Hybrid anode systems differ from the purely galvanic systems. The hybrid treatment (5) consists of applying a temporary impressed current followed by permanent galvanic protection. The principle of this system is that during the initial impressed current phase, active pits are realkalised and this arrests active corrosion and returns the reinforcing steel to a passive state. Following the application of impressed current for a predetermined period of time, the passivity of the steel is then maintained by the sacrificial anode system.

For many years, galvanic anode systems have been installed in conjunction with concrete patch repairs to reduce the occurrence of the incipient anode effect. Normally in these applications, no permanent monitoring system is incorporated and there is no reliable data about the level of the long-term effectiveness or benefit of these anodes. The installation of galvanic anodes has been viewed as an additional low-cost measure to prolong the life of a patch repair.

Recently, galvanic based anode systems including hybrid anode systems have been installed for the corrosion protection of various structures. Based on some initial review of performance data of these systems, it appears that in structures with low corrosion activity and low chloride contamination, these systems offer some level of protection for a period of time after system commissioning.

Galvanic anode system after 8 months of operation				
Ref	Natural potential	IO (mV)	System OFF 24 h (mV)	24 h Decay (mV)
1	-248	-381	-326	55
2	-263	-383	-327	56
3	-274	-484	-404	80
4	-274	-478	-443	35
5	-242	-370	-336	34
6	-177	-245	-198	47

Fig. 1. Performance data from a galvanic anode system installed on a bridge structure after 8 months of system operation.

For galvanic systems, the moisture in concrete significantly affects the current and leads to seasonal changes reflecting wetter and drier conditions. Current output is lower during dry conditions. However, for structures with a high level of chloride contamination, high corrosion activity, and in some cases relatively high resistivity, the level of corrosion protection is limited and the protection criteria in accordance to the applicable standards cannot be achieved in most cases.

3 Areas of improvement for ICCP systems

The key areas of improvement for ICCP systems include the development of simple system designs, robust/heavy

duty components, and systems which are simple to monitor and maintain over their design life. In order to achieve these objectives, based on extensive experience with the installation and monitoring of a large number of ICCP systems, there are various key areas which have been identified related to design, product selection, installation and monitoring and maintenance.

ICCP system after 8 months of operation					
Zone	Ref	Natural Potential (mV)	Instant OFF Potential (mV)	24 hr OFF (mV)	24 hr Decay (mV)
1	11	-355	-420	-293	127
	12	-283	-465	-234	231
	13	-262	-502	-224	278
	14	-324	-554	-274	280
	15	-263	-492	-224	268
	16	-273	-558	-241	317
2	21	-327	-549	-302	247
	22	-261	-509	-229	280
	23	-284	-327	-231	96
	24	-268	-505	-237	268
	25	-276	-532	-235	297
	26	-261	-365	-227	138

Fig. 2. Performance data from an ICCP system installed on a bridge structure after 8 months of system operation.

3.1 Design

There are two main aspects which may impact on the simplification of the design and cost reduction of an ICCP system. These areas are system zoning and design current density.

3.1.1 System zoning

In theory, designing ICCP systems with smaller zones (circuits) provides a higher level of control of the cathodic protection current in various parts of the structure. For large installations, the use of smaller circuits also requires more cabling, more reference electrodes and a larger number of power supply units for the system.

Recently, the authors of this paper were involved in the refurbishment of a relatively large ICCP system installed on Wharves 4 & 5 at the Port of Brisbane (6). As part of the refurbishment work, 13 control units incorporating 172 separate power supply units were moved from underneath the wharf to locations above the wharf. The original system of this ICCP installation included 172 circuits. The new control system included 48 circuits. The substantial reduction in the number of zones (circuits) was achieved by combining smaller circuits with the same exposure conditions and CP current requirements.

Following system re-commissioning, a comparison of CP performance data before and after the reduction in circuits indicates that larger cathodic protection zones offer the same level of corrosion protection and adequate current distribution to the embedded steel. The reduction in the number of circuits had a major impact on reducing the quantity of cables, conduits, power supply units and consequently the cost of ICCP system installation. Providing the embedded reference electrodes are placed as recommended by the applicable standards, larger circuits can be used for ICCP systems without compromising corrosion protection and current distribution.

Combined circuits 2016					
Zone	Section	Ref	IO	24h OFF	24h Decay
			2016	2016	2016
7	4	71A	-160	-26	135
	4	71C	-153	-39	115
	4	72A	-346	-197	149
	4	72C	-245	-83	162
	4	73A	-228	-60	168
	4	73C	-126	-7	119
	4	74A	-218	-71	146
	4	74C	-217	-53	164
	9	71A	-294	-126	168
	9	71C	-284	-164	120
	9	72A	-288	-110	178
	9	72C	-299	-155	144
	9	73A	-212	-91	121
	9	73C	-251	-85	165
	9	74A	-498	-257	241
	9	74C	-241	-137	104

Fig. 3. Table showing system performance using 4 combined circuits (71, 72, 73 and 74) after system refurbishment.

3.1.2 Current density

The design current density for existing reinforced concrete structures is 20 mA/m² of steel surface. Based on data retrieved from a large number of operating CP systems, in some cases the actual operating current density was significantly lower than the actual design current density.

The required current density to achieve protection and meet the protection criteria as defined in the applicable standards is related to chloride content, concrete resistivity, the level of corrosion activity, exposure conditions and steel density. The only possible method to determine the required current density is to perform a current injection test at one or several areas of the structure using a temporary power supply unit. The results from the current injection test can be obtained

immediately by measuring the potential shift of the embedded steel after a short period of time from impressing CP current.

4 Separate circuits 1999					
Zone	Section	Ref	IO	24h OFF	24h Decay
			1999	1999	1999
71	4	71A	-257	-80	177
71	4	71C	-266	-40	226
72	4	72A	-265	-93	172
72	4	72C	-255	-83	172
73	4	73A	-295	-82	213
73	4	73C	-261	-62	199
74	4	74A	-253	-90	163
74	4	74C	-280	-102	178
71	9	71A	-328	-144	184
71	9	71C	-275	-110	165
72	9	72A	-230	-91	139
72	9	72C	-272	-128	144
73	9	73A	-308	-110	198
73	9	73C	-328	-76	252
74	9	74A	-289	-117	172
74	9	74C	-280	-100	180

Fig. 4. Table showing system performance using 4 separate circuits based on the original design.

Zone	Design Current @20mA/m ² of steel surface area mA	Initial Jun 2016 mA	Feb 2018 mA	Jun 2018 mA
1	504	250	200	150
2	504	300	240	220
Current reduction				
Z1 mA	20	9.92	7.93	5.95
Z2 mA	20	11.9	9.52	8.73

Fig. 5. Table showing current reduction after 2 years of system operation.

The outcome from this test may in some cases reduce the design current density from the default 20 mA/m² of steel surface to a lower figure resulting in a major reduction of anode requirement, reduction of power supply unit capacity and consequently major cost reductions for installing the ICCP system. Below is a typical example of a current injection test showing data of the potential shift after a few minutes following

current injection. This test was performed to select the optimum spacing for the anodes.

Pier 30, Pile 6 MRB					
L	Natural Potential	IO	Potential Shift	A	T
	mV	mV	mV		
1	-364	-525	-161	●	●
2	-362	-484	-122	●	●
3	-332	-601	-269	●	●
4	-345	-634	-289	●	●
5	-344	-620	-276	●	●
6	-365	-650	-285	●	●
7	-425	-522	-97	●	●
1	-329	-460	-131	●	●
2	-268	-458	-190	●	●
3	-309	-541	-232	●	●
4	-390	-638	-248	●	●
5	-390	-648	-258	●	●
6	-422	-598	-176	●	●
7	-443	-591	-148	●	●
1	-287	-394	-107	●	●
2	-281	-460	-179	●	●
3	-312	-511	-199	●	●
4	-356	-551	-195	●	●
5	-350	-527	-177	●	●
6	-380	-538	-158	●	●
7	-429	-514	-85	●	●

Fig. 6. Table showing current injection test results used to determine anode spacing.

3.2 Anode installation

In Australia, large sections of the CP systems protecting wharves and bridges are installed in tidal and splash zones and have anode design current densities not exceeding 110 mA/m². 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.

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

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 atmospheric zone 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 locations exposed to water.

Recent research at the University of New South Wales (7) confirms that the anode embedment methods currently in use by the industry in Australia, often combined with poor workmanship, allow water ingress to the ribbon anode, and these are the primary causes of acidification. The research also confirms that the application of a cementitious waterproofing coating (which minimises water ingress to the ribbon anode), can limit or stop the occurrence of grout acidification problems in existing ICCP installations.

The pictures below show a cross section of a reinforced concrete element protected by 4 ribbon anode strips and subjected to an accelerated CP application equivalent to 15 years of system operation at 20 mA/m² of steel surface. Figure 7 picture 1 shows the impact of water ingress and grout acidification for two anodes and figure 7 picture 2 indicates that proper encapsulation of the anode preventing water ingress eliminates the grout acidification problem caused by external water ingress.

3.3 Junction boxes

Junction boxes which are installed in areas of water exposure are normally specified with Ingress Protection (IP) suitable for such exposure. It is the author's experience that regardless of the IP protection of any enclosure, such protection is likely to be compromised during the design life of the CP system when the enclosure is installed in an area susceptible to 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 and thus allowing water ingress.
- Failure of the rubber seal cover of the junction boxes; and
- Failure of the sealant applied around the conduit entries.
- Damage to cables/terminals connections in junction box.

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.



Picture 1

Picture 2



Picture 3

Fig. 7. Picture 1 shows the impact of water ingress and grout acidification for 2 anodes. Picture 2 shows that proper encapsulation of anodes eliminates grout acidification. Picture 3 shows ribbon anode installed for bridge piles with additional protection to eliminate water ingress to anodes.

3.4 Power supply units

Various types of control systems have been installed in Australia in 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 after 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 half-yearly/yearly testing and adjustment of the system (including an inspection of the structure), is sufficient for the adequate long-term monitoring and maintenance of the CP system.

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.

With the advancement in technology in the past two decades, it has often seemed logical for asset owners to install increasingly sophisticated control systems for the monitoring of their CP systems. However, most of the commercial systems that are currently available (while offering various communication and remote testing functions), lack the required durability, can be complex to operate, and often require a high level of technical support for maintenance and repairs. 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 over the long-term. The major maintenance costs are normally associated with replacement of the power supply unit, in cases of major water damage to junction boxes or for the repair of major grout acidification problem.

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 a CP 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:

- A basic and heavy-duty modular power supply unit allowing replacement of components when required without any special programming.
- An interruption facility providing the means for performing instant OFF measurements of the reference electrodes.
- A data logging facility (typically required for large systems only).
- Reliable web-based remote monitoring or standard SCADA connectivity for functional checks only (current for each circuit). This is required for installations in remote locations 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.

Recent improvements in solar technology have allowed the delivery of solar cathodic protection current to small and medium size structures and this eliminates the need for 240 VAC mains power and the use of high cost and high maintenance transformer rectifier power supply units. The use of solar power to deliver low voltage CP current combined with the use of basic, heavy duty and robust DC power supply units may offer a new approach for major cost reductions and simplification of operating impressed current CP systems.

4 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, engineers and consultants operating in the field of cathodic protection must ensure that the optimum design, materials selection, installation and monitoring activities are carried out properly and professionally.

Various aspects of cathodic protection of steel in concrete structures are detailed in international and Australian standards and are 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 and 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.

The failure to design simple and heavy duty ICCP systems for the corrosion protection of reinforced concrete structures will open the door for the preference of less effective galvanic anode systems which cannot achieve the applicable protection criteria and are more costly and less effective for the long-term corrosion protection of infrastructure assets.

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