CONSIDERATIONS AND CHALLENGES ASSOCIATED WITH MONITORING IMPRESSED CURRENT CATHODIC PROTECTION SYSTEMS

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SUMMARY: Impressed current cathodic protection (ICCP) for reinforced concrete structures is a proven technology which has provided long-term corrosion protection to large numbers of bridges and wharves globally and across Australia.

One of the main factors related to the effectiveness of ICCP systems is the correct monitoring and maintenance of these systems. Ongoing adjustments of cathodic protection current over the life of a system based on the outlined protection criteria in global and Australian Standards is essential for achieving optimal long-term corrosion protection.

Some of the challenges associated with monitoring ICCP systems include accurate data retrieval for current adjustment from structures located in tidal areas and eliminating the risk of overprotection for prestressed concrete structures. For prestressed concrete structures subject to large tidal variations, the added complexity of monitoring necessitates the need for control systems with additional capabilities such as remote access and accurate data acquisition.

This paper presents operational data from ICCP systems installed on reinforced and prestressed concrete structures located in atmospheric and tidal zones. The data presented in this paper highlights key issues related to monitoring of such systems. These issues include the type of reference electrodes, the need for ongoing calibration procedures for embedded reference electrodes in concrete in certain applications, and the selection of control systems which allow for accurate data acquisition required for performing monitoring and adjustment of the cathodic protection system.

Keywords: Cathodic Protection, CP, Corrosion, Concrete, Prestressed, Reference Electrode

1. Introduction

Electrochemical applications such as cathodic protection have been utilised as a standard and reliable technique for the long-term corrosion protection of structures located in marine environments and susceptible to chloride-induced corrosion.

A large number of impressed current cathodic protection (CP) systems in concrete have been installed in Australia during the past 35 years. The majority of these systems have been installed in accordance to International Standards [1, 2], up until the issue of Australian Standard AS 2832.5 [3].

The International and Australian Standards for cathodic protection in concrete provide guidelines relating to the assessment and repair of reinforced concrete structures, CP system components, installation procedures, design, commissioning, and the protection criteria for CP system operation and adjustments.

The aim of the paper is to present various considerations associated to the monitoring of impressed current cathodic protection systems.

The main issues which may impact on the accurate and effective monitoring of CP systems are:

1) The type and locations of reference electrodes and monitoring sensors within the concrete elements protected by the CP system.

2) Issues related to the applicability of some protection criteria for CP system current adjustment and performance monitoring.

3) The selection of the appropriate type of control system for various cathodic protection applications.

This paper will highlight the practical challenges associated with monitoring CP systems relating to the above issues. The primary reference document related to this paper is the Australian Standard AS 2832.5 [3].

2. Reference Electrodes and Monitoring Sensors

The most common method for assessing the performance of an impressed current cathodic protection system is with the use of reference electrodes embedded in the concrete. The reference electrodes are installed in the tidal, splash and atmospheric sections of a concrete structure, and in water for the immersed sections of a concrete structure.

For the immersed sections of a concrete structure such as piles, the commonly used reference electrodes are Zinc and Silver/Silver Chloride reference electrodes which are usually installed in the water in the vicinity of the protected elements.

For the atmospheric sections of a concrete structure such as pile caps, piles, headstocks...etc, there are two common types of reference electrodes for embedment in concrete: true half-cell and inert reference electrodes [4].

- The true half-cell reference electrodes most used in Australia are Silver/Silver Chloride reference electrodes and Manganese Oxide reference electrodes.
- The most common inert reference electrodes in concrete are Titanium reference electrodes.

Irrespective of the type of embedded reference electrode used in concrete for monitoring, to obtain accurate readings, it is essential that the interface area between the electrolytic contact of the reference electrode is in full contact with the surrounding mortar. It is also important that the size of the porous plug for a true reference electrode (or the exposed part of an inert reference electrode) is maximised.

For the mortar surrounding the reference electrode, using mortar which is dosed with chloride to replicate the resistance of concrete may provide more accurate data rather than using a clean mortar. Some manufacturers of Silver/Silver Chloride reference electrodes incorporate with each reference electrode package a dosage of salt for adding to the surrounding mortar.

2.1 Determining the locations for reference electrode installation

The location of the reference electrodes is one of the most critical components related to CP system monitoring and adjustment.

In accordance to AS 2832.5-2008 [3], the determination of the extent and location of permanently installed performance evaluation systems shall, for each zone, take into account areas of the concrete structure that have the following characteristics:

(a) Particular sensitivity to under-protection.

(b) Particular sensitivity to excessive protection.

(c) High corrosion risk or activity.

(d) Low corrosion risk or activity.

In order to select the optimum locations for reference electrode installation, external potential mapping of the concrete element to be protected must be performed prior to installation. The reference electrodes must be placed in both high and low corrosion risk areas in order to eliminate the possibility of over-protection and under-protection of the embedded reinforcement. Additionally, the location of a reference electrode must be made with consideration of the location of the anode (positive) connection, as this may impact on the sensitivity of test readings related to over and under-protection.

It is a requirement for a reference electrode to have a dedicated steel connection. The DC negative power return should not be used for potential measurements as the voltage flow within the CP circuit will impact on the readings recorded from the reference electrodes. Each reference electrode should be installed in a location with no direct contact between the mortar surrounding the reference electrode and the rebar.

For the protected concrete element, the size of the potential mapping area must be large enough to identify all areas of low and high corrosion activity with the cathodic protection zone. The number of embedded reference electrodes must be sufficient so that readings are taken in high and low corrosion activity locations, and in areas with vulnerability to under protection and excessive over-protection.

3. Adjustment of ICCP Systems Based on Protection Criteria

The protection criteria based on AS 2832.5 [3] is as follows:

The overriding requirement providing for safe and effective operation of the cathodic protection system is that no instantaneous off steel/concrete potential shall be more negative than -1100 mV for plain reinforcing steel or more negative than -900 mV for prestressing steel with respect to Ag/AgCl/0.5M KCI.

The initial and continuous adjustment of the cathodic protection system shall be based on meeting at least one of the following criteria which are listed in no priority order:

(a) Potential decay criterion. A potential decay over a maximum of 24 h of at least 100 mV from the instantaneous OFF potential.

(b) Extended potential decay criterion. A potential decay over a maximum of 72 h of at least 100 mV from the instantaneous OFF potential subject to a continuing decay and the use of reference electrodes (not potential decay sensors or pseudo reference electrodes) for the measurement extended beyond 24 h.

(c) Absolute potential criterion. An instantaneous OFF potential (measured between 0.1 s and 1 s after switching the D.C. circuit open) more negative than -720 mV with respect to Ag/AgCl/0.5M KCI.

(d) Absolute passive criterion. A fully depolarized potential, or a potential which is continuing to depolarize over a maximum of 72 h after the cathodic protection system has been switched OFF, which is consistently less negative than -150 mV with respect to Ag/AgCl/0.5M KCI.

In order to undertake a correct assessment of a CP system in accordance to the protection criteria in AS 2832.5 [3], the issues which should be considered during the design and installation stage include selection of the type of reference electrode, the locations for reference electrode installation, provision of a methodology for ongoing calibration of the embedded reference electrodes (in certain applications), and the selection of an appropriate control system for the CP system.

3.1 Selection of the type of reference electrodes

While inert reference electrodes have the advantage of offering greater robustness and a longer theoretical life, when such references are embedded in concrete, criterion a) from AS 2832.5-2008 [3] is the only criterion applicable for the assessment of the cathodic protection system. The use of true reference electrodes allows for assessment of the cathodic protection system using all protection criteria in AS 2832.5-2008 [3] and hence, true references offer major advantages for the long-term assessment of the cathodic protection system. As true reference electrodes may have limited life, it is possible to consider the use of a combination of inert and true reference electrodes for one installation.

3.2 Calibration of reference electrodes

For the calibration of reference electrodes installed in water, the calibration process is relatively simple and provides accurate results. Calibrated reference electrodes such as Ag/AgCl/Seawater references (AgCl/AgCl/0.5MKCl) can be used to calibrate reference electrodes in water and the calibrated potential readings can be used for performance assessments of CP systems and current adjustment.

In accordance to AS 2832.5-2008 [3], permanent reference electrodes in concrete shall be checked against a calibrated reference electrode immediately prior to embedment, immediately following embedment, and following installation.

During operation of the cathodic protection system, changes in the concrete chemistry will occur over time and this will affect the stability of permanently embedded references. These variations in readings can be significant and affect readings which relate to absolute values. However, a depolarisation test to confirm protection levels will not be affected provided the reference electrode is stable during the period of depolarisation. Calibration of references will be required routinely if the depolarisation criteria are not used.

Criterion a) and b) will not be impacted by the calibration of embedded reference electrodes. For criterion a), true or inert reference electrodes can be used for assessment, while for criterion b), only true reference electrodes can be used as required by the standard.

For criterion c), the absolute potential criterion can be applied to all concrete elements located in immersed conditions as the permanent reference electrodes located in water can be calibrated against a portable Ag/AgCl/0.5M KCl reference electrode. However, for true reference electrodes located in atmospheric concrete elements, the use of criterion c) and d) may not be accurate as calibration of reference electrodes located in concrete cannot be performed following installation.

The only viable method for reference electrode calibration (following installation) would be with the use of a portable external reference electrode on the concrete surface. While practically this method is unlikely to provide accurate data related to the actual potential of the embedded steel, it will still provide an overall indication of the average potential of the embedded reinforcement. Australian Standard AS 2832.5-2008 [3] correctly identifies the issue related to calibration of reference electrodes and states *"calibration of references will be required routinely if the depolarisation criteria are not used"*, however it does not provide any practical means of accurately achieving such calibration. In this case, criterion a) and b) for atmospheric areas, and criterion c) for immersed areas are the only accurate criteria that should be used for adjustment of cathodic protection current. It is the author's opinion that, criterion c) and d) for atmospheric areas can be assessed as indicative criteria only, however, must not be relied upon for the current adjustment unless a reliable calibration procedure is used.

3.3 Examples of CP system performance assessment

Data extracted from operating cathodic protection systems is presented below to highlight the issues related to the applicability of protection criteria for various circumstances.

Table A - Typical Data for Upper Tidal / Splash Zones
Bridge Structure

Location	Zone	Reference Number	ON Potential Ag/AgCl	IO Potential Ag/AgCl	OFF 24h	OFF 72h	OFF 72h calibrated to Ag/AgCl/ 0.5M KCl	24h Decay	72h Decay	Protection Criteria AS 2832.5-2008			
			mV	mV	mV	mV	mV	mV	mV	a)	b)	c)	d)
Upper Tidal/Splash	Zone 1	1	-446	-427	-336	-315	-369	91	112				
		2	-354	-348	-271	-261	-315	77	87				
		3	-366	-340	-241	-226	-280	99	114				
		4	-667	-582	-436	-405	-459	146	177				
	Zone 2	5	-443	-405	-309	-284	-338	96	121				
		6	-535	-464	-301	-258	-312	163	206				
		7	-301	-262	-160	-130	-184	102	132				
		8	-430	-376	-270	-241	-295	106	135				

Legend:

- Decay criteria not achieved
- Silver/Silver Chloride reference electrode calibration,at commissioning, to Ag/AgCl/0.5MKCl (add -54mV)
- Meeting protection criteria a) and b) of AS 2832.5-2008

Table A shows the performance data from an impressed current cathodic protection system specifically for the upper tidal splash zones of a structure. The installed reference electrodes are Silver/Silver Chloride references and the considered criteria for protection are criterion a) and b) of AS 2832.5-2008 [3]. The protection criteria for zones 1 and 2 (two circuits) can be achieved by maintaining the current in zone 2, and increasing the current in zone 1. In this example, no reference electrode calibration is required as criterion c) and d) are not achieved for any of the reference electrodes.

Table B - Typical Data for atmospheric Zone
Bridge Structure

Location	Zone	Reference Number	ON Potential Ag/AgCl	IO Potential Ag/AgCl	OFF 24h	OFF 72h	OFF 72h calibrated to Ag/AgCl/ 0.5M KCl	24h Decay	72h Decay	Protection Criteria AS 2832.5-2008			
			mV	mV	mV	mV	mV	mV	mV	a)	b)	c)	d)
Atmospheric	Zone 4	10	-273	-231	-69	-56	-110	162	175				
		11	-262	-228	-77	-65	-119	151	163				
		12	-125	-123	-92	-84	-138	31	39				
		13	-244	-234	-105	-85	-139	129	149				
		14	-287	-247	-77	-66	-120	170	181				
		15	-114	-108	-51	-39	-93	57	69				
	Zone 5	16	-374	-319	-81	-66	-120	238	253				
		17	-210	-157	11	34	-20	168	191				
		18	-435	-375	37	98	44	412	473				
		19	-84	-83	-59	-51	-105	24	32				
		20	-207	-204	-64	-43	-97	140	161				
		21	-101	-99	-11	4	-50	88	103				
		22	-269	-178	-83	-71	-125	95	107				
	Zone 6	23	-111	-98	-1	17	-37	97	115				
		24	-96	-94	-14	-3	-57	80	91				
		25	-155	-153	-22	2	-52	131	155				
		26	-250	-219	20	35	-19	239	254				
		27	-153	-151	-50	-29	-83	101	122				

Legend:

- Decay criteria not achieved
- Silver/Silver Chloride reference electrode calibration,at commissioning, to Ag/AgCl/0.5MKCl (add -54mV)
- Criterion d) is based on calibrated value of embedded reference electrodes at commissioning
- Meeting protection criteria a) and b) of AS 2832.5-2008

Table B shows the performance data from the atmospheric zones of an impressed current cathodic protection system. The installed reference electrodes for this structure are Silver/Silver Chloride and the considered criteria for protection are criterion a), b) and d) of AS 2832.5-2008 [3]. Based on the initial calibration data of the reference electrodes to Ag/AgCl/0.5KCl, all reference electrodes meet protection criterion d), and theoretically the system can be switched OFF. However, this decision would require full calibration of the embedded reference electrodes which cannot be accurately performed in practice. In case criterion a) and b) are considered, the current would need to be increased in all 3 zones.

Performing external potential mapping to the concrete elements in the atmospheric zones can provide additional information about the potential of embedded rebar and can be used for overall calibration purposes. However, when marine structures have coating systems, then access can be difficult to perform such calibration testing.

4. Selection of a Control System for Various Applications

The two key functions of a cathodic protection power supply/control system are the capabilities to deliver continuous cathodic protection current to a structure, and the ability of the control system to perform accurate measurements of steel potential. The accurate measurement of IR drop is essential for measuring the potential of the embedded rebar and for system adjustment based on the applicable standards [1, 2 and 3].

While manually operated cathodic protection systems can provide continuous and reliable delivery of cathodic protection current to the protected structures, unfortunately the applicability of these older generation systems for the monitoring of structures located in tidal zones and for structures with prestressed steel may not provide the required outcomes.

AS 2832.5-2008 [3] stated *"It may be appropriate in areas influenced by tidal effects or intermittent moisture exposure to curve fit logged data and extrapolate to a 24-hour period. This may be necessary in areas which are subject to concentration polarization (e.g. limiting rates of oxygen diffusion through water saturated capillary pores of the concrete) or re-polarization due to connection with submerged steelwork at more active potentials during the period of testing. Data should be logged at least at one-minute intervals and the minimum time unaffected by the tidal movement or intermittent moisture effects should be 4 hours"*

When monitoring ICCP systems in locations with significant tidal fluctuations, it is essential that the control system has the capability for remote monitoring which would allow the selection of the testing period based on the tidal conditions, and a data logging facility to be able extract the most relevant data for accurate system monitoring.

The data presented in Tables C and D provides an example of CP system performance data for immersed concrete piles with prestressed reinforcement. Table C presents data recorded at low tide, and Table D presents data recorded at high tide.

Table C - Performance Data for Pre-stressed Steel in Concrete Piles (Low Tide)
Bridge Structure

Zone	Reference	ON Potential (mV) Ag/AgCl	IO Potential (mV) Ag/AgCl	Calibration vs Calibrated Ag/AgCl /0.5M KCl	Calibrated Potential to Ag//AgCl/0.5MKCl (mV)	IO >-720 mV vs AgCl/AgCl/0.5M KCl	IO <-900 mV vs AgCl/AgCl/0.5M KCl
ZONE 1	R1	-661	-642	-9	-651		
	R2	-715	-668	2	-666		
	R3	-712	-672	8	-664		
	R4	-241	-184	-494	-678		
ZONE 2	R5	-258	-224	-485	-709		
	R6	-120	-120	-602	-722		
ZONE 3	R7	-825	-764	48	-716		
	R8	-797	-757	39	-718		
	R9	-572	-522	-366	-888		
ZONE 4	R10	-346	-310	-469	-779		
	R12	-343	-304	-418	-722		
	R13	-321	-283	-512	-795		
ZONE 5	R14	-253	-213	-585	-798		
	R15	-914	-860	84	-776		
	R16	-366	-337	-454	-791		

Legend:

Criterion Achieved

Table D - Performance Data for Pre-stressed Steel in Concrete Piles (High Tide) Bridge Structure							
Zone	Reference	ON Potential (mV) Ag/AgCl	IO Potential (mV) Ag/AgCl	Calibration vs Calibrated Ag/AgCl /0.5M KCl	Calibrated Potential to Ag/AgCl/0.5MKCl (mV)	IO >-720 mV vs AgCl/AgCl/0.5M KCl	IO <-900 mV vs AgCl/AgCl/0.5M KCl
ZONE 1	R1	-737	-717	-9	-726		
	R2	-769	-722	2	-720		
	R3	-767	-727	8	-719		
	R4	-303	-245	-494	-739		
ZONE 2	R5	-327	-293	-485	-778		
	R6	-183	-183	-602	-785		
ZONE 3	R7	-918	-857	48	-809		
	R8	-871	-831	39	-792		
	R9	-659	-609	-366	-975		
ZONE 4	R10	-427	-391	-469	-860		
	R12	-488	-449	-418	-867		
	R13	-379	-341	-512	-853		
ZONE 5	R14	-317	-277	-585	-862		
	R15	-977	-924	84	-840		
	R16	-413	-384	-454	-838		

Legend:

Criterion Achieved

Based on the above data, the following assessment can be made:

- The immersed reference electrodes are Silver/Silver Chloride reference electrodes. These references are calibrated prior testing against a portable Silver/Silver Chloride (Ag/AgCl/0.5MKCl) reference electrode. It is noted that Silver/Silver Chloride reference electrodes in water show major drift, and in this case, calibration is essential to obtain any relevant data.
- The applicable criterion in this case is criterion c) from AS 2832.5-2008 [3] which is subject to no instantaneous OFF steel/concrete potential being more negative than -900 mV for prestressing steel with respect to Ag/AgCl/0.5M KCl.
- This testing was performed remotely exactly at low tide and high tide. It is noted that compliance to the protection criteria is relevant to the tidal variation, and it is highly essential to carry out this testing at both tide levels to ensure full protection.
- In order to accurately perform testing as per maintenance program for a structure (in this case at a frequency of two-month intervals), testing at high and low tide must be carried out and current adjustment must be performed on the basis of the retrieved data at low and high tide. To achieve this, only a remote-control system would be suitable for this application.

5. Conclusions

Selecting the correct type, number and installation locations for reference electrodes is essential for effective CP system monitoring. The cathodic protection current delivery to a structure relies heavily on the suitable positioning of reference electrodes in the protected concrete elements. Further, an adequate number of reference electrodes must be installed for each circuit in appropriate locations to allow for system adjustment and to eliminate any possibility of overprotection or under protection of the embedded rebar.

Constructing CP systems which allow for future calibration of embedded reference electrodes using external potential mapping or an alternative method would allow for optimum monitoring of impressed current cathodic protection systems and the use of all protection criteria from the applicable standards.

Recent developments in high precision digital control buck converters, combined with increasingly reliable components such as industrial computers, modems, routers and switches… etc. has allowed for the manufacturing of advanced and cost-effective control systems for monitoring CP systems. The use of advanced remote-control systems, especially for structures located in tidal zones and/or for monitoring of prestressed concrete structures, is vital for the proper system monitoring.

From a practical perspective and based on the author's experience, for CP systems located in remote geographic locations, the duration for decay testing is often dictated by the travel itinerary of the technician performing the monitoring work. Accurate 24 and 72 hour decay testing based on the requirements of the applicable standards can be best performed if a remote-control access is available for testing.

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.

6. References

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