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CONSIDERATIONS ASSOCIATED WITH THE SELECTION OF ELECTROCHEMICAL PROTECTION SYSTEMS FOR A HIGH-RISE BUILDING IN SYDNEY, AUSTRALIA

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ABSTRACT

Cathodic protection systems for reinforced concrete structures have provided long-term corrosion protection to many reinforced concrete structures in Australia over the past 40 years.

In recent years, galvanic-based cathodic protection has become an area of substantial growth due to its simplicity and low monitoring and maintenance requirements.

The lack of independent detailed information related to the costing, performance, advantages, and disadvantages of galvanic-based and impressed current corrosion protection systems has in many cases led to the selection of unsuitable corrosion protection systems, unable to provide long-term cost-effective corrosion protection solutions.

This paper presents performance data from a recently completed major rehabilitation project of a multi-story building in Sydney, Australia, where both impressed current and galvanic cathodic protection systems have been utilized.

This paper outlines the reasons behind the selection process of the corrosion protection systems and presents the performance data of some of the protection systems post-construction.

This paper aims to assist owners in the selection process of the optimum corrosion protection solution for their assets.

Keywords: corrosion protection, impressed current, cathodic protection, galvanic, incipient anode

INTRODUCTION

The case study presented in this paper is for a 7-story apartment building situated in a beach-front location in Sydney, Australia. The building was constructed circa 1977 and over the years was affected by concrete defects related to chloride ingress from the adjacent sea front.

The building refurbishment works which were carried out in 2020-2022 included concrete repair in conjunction with Impressed Current Cathodic Protection (ICCP), Incipient Anode Galvanic Protection (IAGP), and Sacrificial Anode Cathodic Protection (SACP). In addition to the repair work, the building refurbishment included the installation of new windows and doors, waterproofing, tiling, plumbing, and the application of an external protective/decorative coating.

This paper will provide information related to the condition survey of the building, the repair strategy selected for various elements of the building, details of the installed cathodic protection systems, and performance data of the ICCP and the SACP systems.

PRE-DESIGN INVESTIGATION WORKS

CONDITION SURVEY AND TRIAL APPLICATIONS

The primary causes of the building's defects were chloride contamination of the concrete facade elements, and chloride ingress from the magnesite floor topping into the building's internal floor slabs.

In the 1960s and 70s in Sydney particularly, the use of magnesite as a floor covering was widespread in residential unit development. Since its installation, it has become evident that after a period of 40 years or more, and due to long-term exposure to household moisture and/or water through balcony doors, the magnesite was the source of chloride ingress into the concrete slab, due to leeching of unreacted Magnesium Oxychloride [1]

The level of chloride contamination (and the resulting defects) varied substantially between different elements of the building, and the locations of the defects were dependent on the elevation and orientation of the concrete elements. For the balcony floor slabs, the chloride concentration of 38% of the embedded rebar at the steel level was less than the threshold of 0.4% W/W of cement. the chloride concentration of 35% of the embedded rebar at the steel level was between 0.4% and 1% W/W of cement and the chloride concentration of 27% of the embedded rebar at the steel level was greater than the 1% W/W of cement. The condition survey work included continuity testing for all the embedded rebar located in the various reinforced concrete elements of the building. All the embedded reinforcement within the treated elements of the building were confirmed to be continuous, as such this was one of the main considerations for the design of the various cathodic protection systems.

Because of the large variety of defects due to the building exposure conditions, targeted treatment based on the identified defects and potential future corrosion risk was the key consideration for the overall repair strategy of the building. The recommendations for the building rectification included the implementation of several corrosion protection treatments including Impressed Current Cathodic Protection (ICCP), Sacrificial Anode Cathodic Protection (SACP), Incipient Anode Galvanic Protection (IAGP), and anti-carbonation/anti-chloride coating systems. Verification of the adequacy of the proposed ICCP system to achieve full corrosion protection based on the applicable standards was carried out through the completion of a trial application to one of the balcony slabs and one of the building columns located on the ground floor. The trial applications were performed as a part of the investigation work and indicated that full corrosion protection could be achieved by the various Cathodic Protection systems proposed to all nominated treatment areas.

ASSESSMENT OF REMEDIATION STRATEGY

In general terms, the overall observed and measured corrosion characteristics of the building were categorized as follows:

1. The external balcony slabs and the ground floor building columns suffered from relatively extensive concrete deterioration and reinforcement corrosion.
2. The residential floors building columns suffered from localized spalling and relatively low levels of reinforcement corrosion.
3. The building's internal floor slabs suffered from corrosion and concrete spalling due to chloride contamination due to issues associated with magnesite flooring.
4. The building's car park slabs and soffit had isolated concrete spalling due to chloride induced reinforcement corrosion.

Figure 1: General System Arrangement – Nominated Repairs

ELECTROCHEMICAL PROTECTION SYSTEMS

CATEGORY 1 REPAIRS: IMPRESSED CURRENT CATHODIC PROTECTION (ICCP) SYSTEM

The most exposed elements of the building and the elements which suffered the highest level of chloride contamination and concrete spalling were the external balconies and the ground floor columns, primarily form the presence of salt spray.

For those elements of the building, An ICCP system using Mixed Metal Oxide (MMO) ribbon anodes was installed from the balcony top surface protecting all embedded steel reinforcement in the balcony slab. The ICCP anodes were embedded in the concrete in slot cuts and a subsequent waterproofing, and tiling system was installed on all balconies providing full encasement of the ICCP system within the balcony elements.

The building’s columns suffered from isolated concrete spalling and varied levels of chloride contamination at the reinforcement level. Additionally, half-cell potential mapping was performed for all the building’s columns. Based on the test results, where the ground floor columns which were identified with high corrosion activity and a moderate level of chloride contamination, an ICCP system using discrete MMO anodes was nominated and installed.

In order to eliminate any potential interference between the areas protected by ICCP and SACP systems, typical separation of 350 mm was adopted between the areas protected by different protection systems.

The overall ICCP system was divided into 9 independent circuits. Fifty-nine (59) Silver/Silver Chloride reference electrodes were embedded in the concrete for system monitoring. For each of the 28 balconies, 2 reference electrodes were installed for system monitoring. Based on the exposure conditions of the buildings, the 28 balconies were combined into 8 circuits and the ground floor columns were incorporated in one circuit. Measurement of the current for each of the 29 sub-circuit can be performed from the control system for additional verification of current delivery to each sub-circuit. During subsequent construction work post the installation of the CP system, 4 reference electrode cables were damaged due to post trades, and as such the system is now monitored using Fifty-five (55) functional embedded reference electrodes.

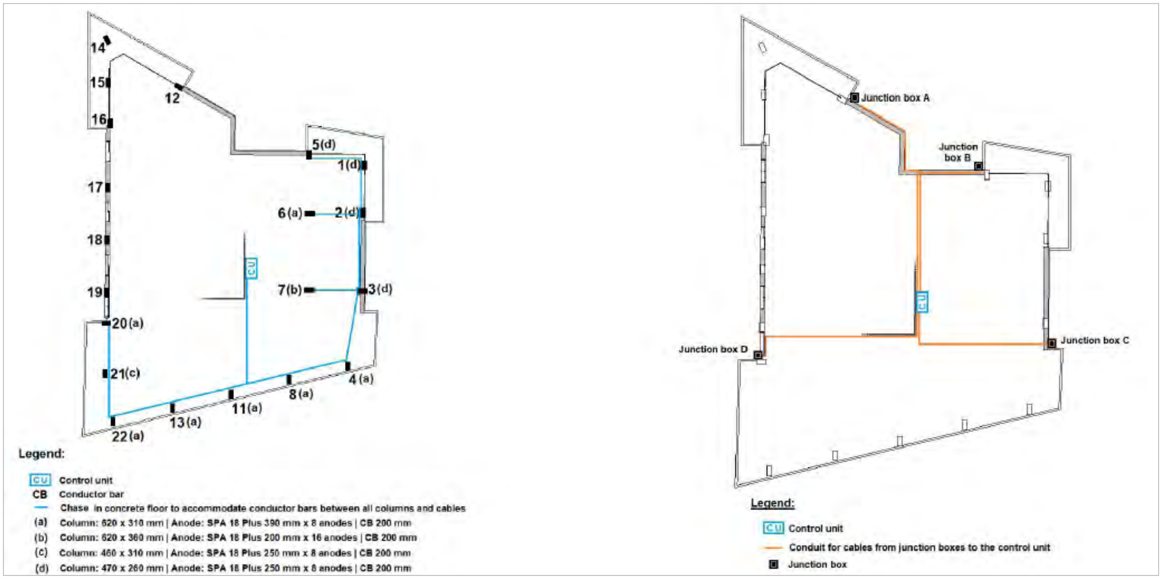

Figure 2: ICCP Cabling Layout

It should be noted during the design phase of the works that the location of the reference electrodes is one of the most critical components related to CP system monitoring and adjustment.

In accordance with AS 2832.5-2008 [2], the determination of the location of permanently installed reference electrodes for each zone shall take into account areas the concrete structure has with 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.

To select the optimum locations for reference electrode installation, external potential mapping of the concrete element to be protected by the ICCP system was performed before installation. The reference electrodes were placed in both high and low corrosion risk areas to eliminate the possibility of over-protection and under-protection of the embedded reinforcement. Additionally, the location of a reference electrode was selected with consideration of the location of the anode (positive) connection in each circuit to eliminate the possibility of under and over-protection. Furthermore, no reference electrodes were installed in any of the repair areas.

PROGRESSIVE ICCP SYSTEM ENERGIZATION

One of the key requirements of installing ICCP systems in buildings is the progressive energizing of the system during the construction period. The primary reason for this requirement is that various building activities such as the installation of doors, windows, and tiles may damage some of the ICCP system components and rectification can be planned and executed while access is available during the construction period.

For the subject system, progressive energizing using a portable battery-operated power supply unit was performed for all circuits of the ICCP system and formed a key component of the contractor’s accredited Quality Assurance (QA) procedures. Various faults mostly caused by cable damage were identified and were rectified during the construction period. All faults related to the anode and steel cables were rectified. Unfortunately, the faults related to the four (4) embedded reference electrodes could not be rectified due to the extent of the post trade works that were completed at the time of identification.

CATEGORY 2 REPAIRS: SACRIFICIAL ANODE CATHODIC PROTECTION (SACP) SYSTEM

For the building columns to the residential floors, moderate corrosion activity was identified in localized areas subject to the exposure conditions of the building. For those columns, a localized SACP system using galvanic anodes installed in drilled holes in the concrete was selected to provide targeted corrosion protection to the embedded reinforcement.

Due to the ease of installation, it was deemed that in areas that are yet to exhibit extensive reinforcement corrosion, yet that are susceptible to ongoing deterioration due to environmental conditions, this type of system would provide additional long-term durability to the nominated areas in the most cost effective manner

Similarly, however from a constructability and practicality perspective, one of the major advantages of using SACP in the vicinity of doors and windows, instead of an ICCP system, is the high unlikelihood of stray current corrosion to embedded metallic elements used to fix the windows and the doors in place, in areas immediately adjacent to nominated protected areas.

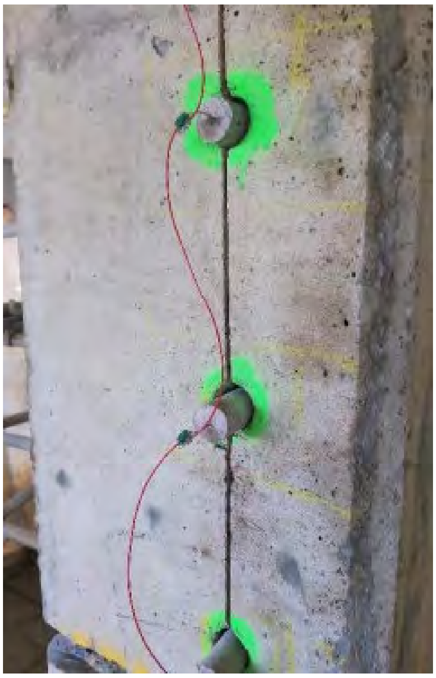

Figure 3: Installation of discrete galvanic anodes

CATEGORY 3 REPAIRS: INCIPIENT ANODE GALVANIC PROTECTION (IAGP) SYSTEM

The building's internal floor slabs suffered from chloride-induced corrosion caused by magnesite topping, as detailed above. Through the leaching of unreacted Magnesium Oxychloride, the presence of chlorides led to steel reinforcement corrosion in the concrete slabs, resulting in cracking, spalling, and 'lumping' of the concrete below the floor covering.

The repair strategy for the internal magnesite-affected areas of the building included the removal of chloride-contaminated concrete behind the reinforcement within damaged areas, performing conventional concrete repair for those areas, and the installation of galvanic anodes at the edge between the repair area and existing sound, nonetheless chloride contaminated concrete. Generally, for floor internal areas with a high level of chloride, the options for corrosion protection are relatively limited due to installation, and preservation of installed components practicalities. Furthermore, once any remnants of magnesite flooring is removed, required for any CP installations, the primary source of chlorides is removed. Hence the adopted option was the only practical solution in this case.

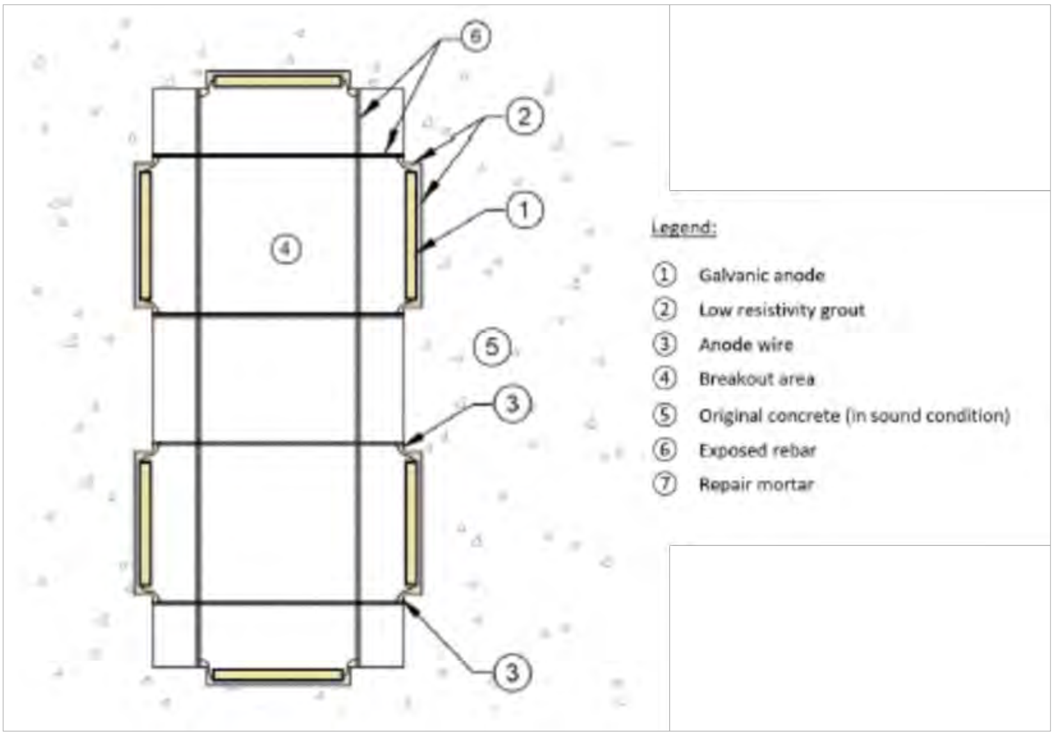

Figure 4: Incipient Anode Galvanic Protection Arrangement

Furthermore, for the building’s car park slabs and soffit areas which suffered from isolated concrete spalling due to reinforcement corrosion, galvanic anodes were installed at the edge of the patch repair areas to extend the life of the patch repair and reduce the potential impact of incipient anode corrosion between the repaired and unrepaired areas.

Where structurally viable at the car park slab, glass fiber rebar was used to replace existing corroding steel reinforcement and thus eliminating the need for the use of any corrosion protection system. No monitoring was installed for the IAGP system.

SYSTEM CHARACTERISTICS

GALVANIC ANODES

New generation galvanic anodes were selected for corrosion protection in this building. The main characteristics of these anodes are the relatively large zinc surface area and the elongated and slim shape of the anodes allowing easy embedment in concrete, when consider reinforcement orientation, density, and congestion characteristics.

It is believed that the shape of the anodes would offer adequate current distribution and more sustainable current output over the life of the system. The basic design philosophy for this application was to install anodes at a closer spacing of 175mm in targeted applications, as opposed to ICCP anodes that were installed and 300mm spacings. All anodes were encased with low resistivity repair mortar. Potential measurements of steel were carried out before and after anode installation to verify proper anode installation and initial performance.

For all tested areas of galvanic anode application, it was measured that an initial and substantial potential shift to more negative potentials was recorded at all anode locations.

ICCP CONTROL SYSTEM

In past years, the maintenance and monitoring requirements associated with ICCP control systems were one of the main disadvantages of using ICCP technology in Australia. Many asset owners selected alternative and less effective corrosion protection solutions to eliminate the costs of ongoing maintenance and monitoring.

The first generation of ICCP control systems included basic manually operated phase-control systems. These systems provided continuous and reliable delivery of cathodic protection current to many structures in Australia. Due to recent technological advancements, much of the original phase control system hardware is no longer manufactured because of superseded system components. In addition, the non-modular design of phase control systems added complexity to the serviceability of these systems. These systems also required a high frequency of site attendance for functional checks and performance testing and had consequently high monitoring costs.

The second generation of ICCP control systems included highly advanced proprietary systems with full remote monitoring and control capabilities including remote facilities for depolarisation testing and various levels of alarm functionality.

The high level of maintenance associated with maintaining the complex electronic components resulted in higher maintenance costs for asset owners and frequent interruptions in cathodic protection current delivery to the structures. The major issue with these systems was that they were fully reliant on their supplier’s software and were designed with a central computer. Any computer or communications fault would lead to the failure of the entire system and the interruption of the cathodic protection current delivery.

In more recent years, technological developments led to the introduction of a new (third) generation of ICCP control systems. Unlike the previous generation, these systems are built utilizing existing, reliable, and commercially available components.

The key advantage of the third generation of control systems is that the systems are modular and are built using an open non-proprietary platform, allowing for future user upgradability. These systems are more reliable, and although each component is equipped with full remote monitoring and control functionality, each component operates independently unlike the older generations of systems. In the unlikely event of a communication outage, the CP’s current delivery and the corrosion protection of the structure is not be affected.

Australia has been one of the leading countries in the introduction and use of this generation of ICCP control systems for new structures and replacement of aging first and second-generation ICCP systems in existing structures.

The reliability of this technology and the lower maintenance and monitoring costs eliminate the perceived disadvantages of ICCP systems associated with high ongoing maintenance and monitoring costs.

This technology was used for the cathodic protection current delivery to the subject building. The system provides 24/7 functional checks of current delivery with an alarm function and the capability for remote performance testing and cathodic protection current adjustment.

SYSTEM ASSESSMENT

ICCP PERFORMANCE DATA

Seen following in figure 5 is the most recent performance assessment data, taken in September 2022, indicating full corrosion protection in accordance with the applicable Australian standard for ICCP systems in concrete structures.

Input Data			Performance Data									
Zone	ID	Design Current	Circuit (mA/V)		ON Potential	IO Potential	24h OFF Potential	24h Decay	72h OFF Potential	72h Decay	Criteria	Adjust.
		mA	mA	V	mV	mV	mV	mV	mV	mV		mA
1	1	1331	210	1.58	-697	-550	-277	273	-238	312	🟩	170
	2				-544	-461	-274	187	-249	212	🟩	
	3				-692	-477	-155	322	-145	332	🟩	
	4				-520	-408	-203	205	-193	215	🟩	
	5				-536	-451	-298	153	-290	161	🟩	
	6				-736	-507	-207	300	-202	305	🟩	
	7				-746	-469	-208	261	-202	267	🟩	
	8				-743	-479	-209	270	-188	291	🟩	
2	9	998	150	1.64	-668	-508	-84	424	-84	424	🟩	110
	10				-833	-529	-109	420	-119	410	🟩	
	11				-730	-532	-181	351	-162	370	🟩	
	12				-660	-420	-157	263	-163	257	🟩	
	13				-684	-468	-98	370	-115	353	🟩	
	14				-747	-483	-70	413	-63	420	🟩	
3	15	1206	200	1.69	-603	-514	-327	187	-301	213	🟩	150
	16				-661	-484	-146	338	-147	337	🟩	
	17				-733	-494	-186	308	-158	336	🟩	
	18				-613	-539	-228	311	-207	332	🟩	
	19				-754	-568	-89	479	-103	465	🟩	
	20				-675	-581	-274	307	-239	342	🟩	
	21				-738	-594	-329	265	-290	304	🟩	
	22				-753	-562	-222	340	-207	355	🟩	
4	23	904	85	1.34	-573	-423	-84	339	-103	320	🟩	50
	25				-668	-472	-142	330	-107	365	🟩	
	26				-675	-478	-159	319	-133	345	🟩	
	27				-565	-459	-122	337	-121	338	🟩	
	28				-586	-433	-221	212	-204	229	🟩	
5	29	1352	220	1.5	-667	-456	-104	352	-102	354	🟩	220
	30				-638	-454	-119	335	-120	334	🟩	
	31				-403	-363	-266	97	-263	100	🟩	
	32				-422	-355	-188	167	-176	179	🟩	
	33				-725	-530	-197	333	-186	344	🟩	
	34				-744	-491	-77	414	-82	409	🟩	
	35				-804	-538	-89	449	-115	423	🟩	
	36				-659	-490	-193	297	-145	345	🟩	
6	37	1014	100	1.21	-539	-404	-128	276	-136	268	🟩	80
	38				-572	-392	-115	277	-71	321	🟩	
	39				-499	-382	-84	298	-53	329	🟩	
	40				-485	-351	-111	240	-103	248	🟩	
	41				-533	-359	-26	333	-71	288	🟩	
	42				-466	-350	-39	311	-70	280	🟩	
7	43	1851	180	1.35	-601	-494	-228	266	-211	283	🟩	150
	44				-571	-447	-169	278	-166	281	🟩	
	45				-530	-444	-280	164	-260	184	🟩	
	46				-577	-428	-222	206	-217	211	🟩	
	47				-606	-465	-171	294	-175	290	🟩	
	48				-498	-426	-179	247	-185	241	🟩	
8	51	1388	240	1.72	-364	-314	-184	130	-180	134	🟩	220
	52				-760	-484	-187	297	-159	325	🟩	
	53				-755	-517	-248	269	-232	285	🟩	
	54				-684	-502	-211	291	-205	297	🟩	
	55				-852	-594	-160	434	-157	437	🟩	
	56				-611	-448	-152	296	-151	297	🟩	
9	57	490	220	4.08	-785	-361	-86	275	-90	271	🟩	200
	59				-382	-257	-89	168	-94	163	🟩	

Figure 5: ICCP system performance assessment - September 2022

SACP PERFORMANCE DATA

No permanent reference electrodes were installed for the SACP system. To verify that the galvanic anodes are installed correctly and obtain data related to the initial performance of the SACP system, external potential mapping was carried out using a portable Ag/AgCl reference electrode. The testing measured the natural potential of embedded rebar prior to installation of the anodes, and then secondary testing was performed in the same locations thirty days after anode installation. The data below shows the potential shift in 30 test locations. While it is not expected that these magnitudes of potential shift will be maintained for the life of the system, the shifts do provide an indication of the level of initial performance.

SACP - Potential shift after 30 days							
Potential measurement using external portable Ag/AgCl reference electrode							
All readings are in mV							
Column 22							
Natural potential (NP)			Potential (ON)			Shift (ON-NP)	
-481	-417		-603	-566		-122	-149
-411	-372		-584	-661		-173	-289
-369	-385		-677	-690		-308	-305
-356	-438		-750	-689		-394	-251
-379	-434		-630	-539		-251	-105
-392	-399		-650	-482		-258	-83
-365	-298		-597	-480		-232	-182
Column 8							
Natural potential (NP)			Potential (ON)			Shift (ON-NP)	
-178	-190		-280	-284		-102	-94
-201	-214		-292	-366		-91	-152
-206	-178		-449	-544		-243	-366
-208	-146		-408	-442		-200	-296
-211	-162		-492	-536		-281	-374
-180	-171		-427	-469		-247	-298
-234	-190		-403	-365		-169	-175
-200	-313		-299	-514		-99	-201

Figure 6: SACP system performance assessment

CONCLUSION

Through the project it was demonstrated how different electrochemical protection systems were used for the subject building. The selection process of the protection system was based on the initially measured and assessed level of corrosion activity, the results of trial applications, and considerations related to the maintenance requirements for these systems in a residential building.

The ICCP system was selected for all areas with high levels of corrosion activity due to design life, and the anticipated rate of future deterioration. The SACP system was selected for the elements with moderate corrosion activity and was installed at targeted locations to provide local corrosion protection, due to practicality, anticipated future deterioration rates, and cost efficiencies.

For the ICCP system, the residual effect was considered in the design process and the design life of the ICCP system. Based on data extracted from multiple operating ICCP systems [3], the ICCP system will substantially improve the corrosion resistance of embedded reinforcement and the cathodic protection current required to maintain protection based on the applicable standards will be substantially reduced over time. On this basis, and providing the system is monitored regularly, no further corrosion is expected in the ICCP protected areas.

The Sacrificial Anode Cathodic Protection (SACP) and the Incipient Anode Galvanic Protection (IAGP) were installed for additional corrosion protection. The design assumption was based on that the effectiveness of the anodes may vary substantially between different locations based on chloride content, level of corrosion activity and concrete resistivity. Due to the nature of the SACP applications (targeted applications and global installation areas), it was assumed that localised corrosion may occur in isolated locations and dealing with the repair of such localised areas was incorporated into the initial project budgeting considerations, and in the ongoing building maintenance program.

Corrosion protection systems in concrete are an ideal technology for long-term corrosion protection and preservation of infrastructure. A properly designed and installed corrosion protection system can provide long-term corrosion protection to structures, whilst allowing for minimal maintenance costs.

Impressed current cathodic protection technology for steel in concrete has now reached maturity and can be utilized as a standard and reliable technique for the long-term corrosion protection of structures suffering from chloride-induced corrosion.

Galvanic cathodic protection is currently an area of substantial growth because of its simplicity. Properly designed and installed galvanic anode systems can play a major role in the corrosion protection of concrete structures. The key aspects that require consideration are the selection of a galvanic anode system with a proven record of performance, adequate verification of continuity of embedded rebar in the galvanic anode zone of influence, and the encapsulation of anodes with low resistivity cementitious mortar to maintain a higher magnitude of galvanic current over an extended period.

The proper selection of corrosion protection systems, conducting trials where appropriate to verify the effectiveness of the selected system in providing the optimum protection, and the proper system installation are essential components for providing the long-term and cost-effective solution for infrastructure corrosion protection. Without these considerations and successful implementation, it is unlikely that full protection and efficiency of any designed system will be realized.

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