Assessment of the performance of ICCP, hybrid anode and sacrificial anode systems operating on concrete bridges and structures in NSW, Australia based on potential criteria

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Abstract. The bulk of reinforced concrete bridges and wharves along the Australian coastline are exposed to the risk of chloride induced corrosion. For many of these structures, concrete deterioration has occurred due to chloride induced corrosion. As part of the long-term maintenance strategy for reinforced concrete bridges and structures in New South Wales, various types of corrosion protection systems were installed on bridges and wharves over the past thirty years. The majority of the early installations were impressed current cathodic protection (ICCP) systems, and in recent years, hybrid anode cathodic protection (HACP) and sacrificial anode cathodic protection (SACP) systems have increasingly been used for corrosion protection. A comprehensive performance monitoring program is in place for some of these operating corrosion protection systems based on the corrosion protection system type. The program complies with the current Australian Standard for performance monitoring, including functional checks at three-month intervals and performance testing at six-month intervals for all ICCP systems. For the sacrificial and hybrid anode systems, the program includes annual testing to obtain information related to the level of corrosion protection provided by the systems. The overall aim of the program is not only to ensure that all corrosion protection systems are monitored and maintained based on the applicable standards, but also to assess the effectiveness of various corrosion protection technologies for future implementation through the yearly system audit. This paper will summarise the performance of some of the ICCP, HACP and SACP systems operating in New South Wales, Australia. This information will be useful for asset owners who need to select the most efficient corrosion protection technology based on the expected service life of their assets.

1 Introduction

The past 30 years have seen extensive use of Impressed Current Cathodic Protection (ICCP) across numerous coastal bridges and wharves in Australia, aimed at protecting reinforced concrete structures from chloride induced corrosion in marine environments, particularly on bridges constructed before 1994 [1]. More recently, Sacrificial Anode Cathodic Protection (SACP) and Hybrid Anode Cathodic Protection (HACP) systems have gained popularity due to their reduced monitoring and maintenance demands [2]. For many years, galvanic anodes have been incorporated into concrete patch repairs to mitigate the risk of incipient anode, and in turn extend the lifespan of the conventional concrete repairs. Over the last 10 to 15 years, SACP and HACP systems have increasingly been adopted as full-scale corrosion protection solutions in Australia.

The design, installation, and monitoring of ICCP, SACP, and HACP systems in Australia follow the guidelines set out in the Australian Standard AS 2832.5 – 2008 (R2018) [3]. Additionally, the cathodic protection criteria in AS 2832.5 align with the protection criteria of AMPP Standard SP 0290-2019 [4] and ISO 12696:2022 [5].

This paper provides an analysis of the theoretical principles behind ICCP, SACP, and HACP technologies. It also summarises performance data from cathodic protection systems implemented on 21 bridges in New South Wales (NSW), Australia, which have been in operation for several years. Using this data, the paper evaluates the effectiveness of these technologies in mitigating corrosion on these bridges, focusing on their adherence to the protection criteria specified in the relevant Australian standard for cathodic protection.

2 Background Information

The ICCP system utilises an external anode embedded in the concrete to protect steel reinforcement. When cathodic protection current is applied, hydroxyl ions are generated at the steel-concrete interface, promoting the formation of a stable passive film on the steel surface. This protective oxide layer prevents the formation of anodic and cathodic sites, effectively halting corrosion.

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SACP systems use zinc anodes, connected to the reinforcing steel. The potential difference between the zinc and steel creates a protective current that flows from the zinc to the steel. Various galvanic anodes are specifically designed for concrete structures and come with proprietary backfill material to accommodate the byproducts of anodic electrochemical reactions.

Two types of HACP systems have been implemented in Australia. The majority of these installations use type 1 hybrid anode systems, which serve as both impressed current and galvanic anodes. Initially, a temporary power source drives current from the installed anode to re-passivate corroding steel. After this phase, the anode is connected directly to the steel, providing galvanic protection.

Type 1 hybrid anode systems deliver a combination of pit-realkalisation (to arrest corrosion) followed by supplementary galvanic protection (to maintain concrete's high pH and in turn long-term reinforcement steel passivity). Both treatments are provided by permanently installed zinc anodes. The system includes negative connections welded to the reinforcement and embedded reference electrodes for monitoring.

During the impressed current phase, the system applies protective current through zinc anodes, generating hydroxyl ions that neutralise acid in corrosion pits (pit-realkalisation). The applied voltage also repels chloride ions from the steel. The system delivers a minimum criterion of 50 kC per square metre of reinforcement at 9 volts [6-12].

Once the impressed current phase is complete, the system transitions to the galvanic phase, where zinc anodes provide a small ongoing current through galvanic corrosion, maintaining the passive environment at the steel surface and preventing chloride diffusion and corrosion re-initiation [9, 13-16].

Type 2 hybrid anode systems, introduced later, integrate both the impressed current and galvanic phases within a single anode unit encased in activated cementitious mortar. The system automatically transitions from the impressed current phase (Phase 1) to the galvanic phase (Phase 2) with a built-in battery delivering the initial passivation current, ensuring independent operation of each phase.

In New South Wales, a comprehensive monitoring program is in place for ICCP, SACP, and HACP systems. ICCP systems are monitored to ensure they remain operational, and their performance is adjusted according to standards. SACP and HACP systems are regularly monitored to assess performance and guide future implementations for corrosion protection.

This paper summarises the performance of 21 ICCP, HACP, and SACP systems in New South Wales, Australia, providing valuable insights to the asset owners for selecting the best corrosion protection technology.

3 Protection Criteria

The protection criteria to AS 2832.5 – 2008 (R2018) is as follows [3]:

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 KCl.

The system adjustment shall be based on meeting one of the following criteria:

a) A potential decay criterion over a maximum of 24 h of at least 100 mV from Instant OFF.

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

c) Absolute potential criterion. An Instant OFF potential more negative than –720 mV with respect to Ag/AgCl/0.5M KCl.

d) Absolute passive criterion. A fully depolarised potential, or a potential which is continuing to depolarise 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 KCl.

Compliance with at least one of the above criteria shall also be maintained on a continuous basis for the life of the system.

This paper's performance assessment is based on the above criteria, which are widely accepted and applied by corrosion engineers worldwide. If these criteria do not confirm adequate protection, further testing must be conducted to ensure that the corrosion rate remains insignificant. While some engineers have utilised corrosion rate measurements for this purpose, implementing such measurements is more complex compared to using the established criteria. The interaction of various environmental factors, such as chloride content, pH at local anodic areas, temperature, oxygen levels, and humidity, complicates corrosion rate measurements. As a result, the use of potential-based criteria for assessing the performance of steel in concrete has been widely implemented, driven by compliance requirements, practical experience and simplicity. Corrosion rate measurement as a protection criterion is beyond the scope of this paper.

4 Design Considerations

For ICCP systems, the default design current density is typically set at 20 mA/m² of steel surface area unless a current injection test is performed during the design phase. Conducting a current injection test is highly beneficial for validating and optimising the design, as it allows the design current density to account for additional critical factors beyond steel density, such as chloride concentrations, concrete resistivity, and corrosion activity. These parameters significantly influence the required current density and the long-term efficacy of corrosion protection.

A current injection test can be completed within 2-3 days as part of the design process. This test provides essential data to optimise the design and mitigate risks associated with assumptions made during the initial design phase.

Below is typical data from a current injection test conducted on a bridge located in a marine environment suffering from chloride-induced corrosion.

Table 1. Current Injection Test

	Position						
Potential (mV)	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Row 1							
Potential of embedded steel measured at the concrete surface by RE @ 300 mm spacing							
Natural potential	-189	-175	-195	-245	-245	-177	-171
Instant OFF potential	-360	-360	-409	-379	-416	-332	-367
Potential shift	-171	-185	-214	-134	-171	-155	-196
Row 2							
Potential of embedded steel measured at the concrete surface by RE @ 300 mm spacing							
Natural potential	-177	-169	-206	-251	-231	-196	-148
Instant OFF potential	-305	-383	-353	-354	-441	-406	-383
Potential shift	-128	-214	-147	-103	-210	-210	-235
Row 3							
Potential of embedded steel measured at the concrete surface by RE @ 300 mm spacing							
Natural potential	-165	-196	-200	-262	-228	-171	-180
Instant OFF potential	-388	-413	-352	-360	-442	-369	-375
Potential shift	-223	-217	-152	-98	-214	-198	-195
Row 4							
Potential of embedded steel measured at the concrete surface by RE @ 300 mm spacing							
Natural potential	-196	-246	-221	-273	-235	-203	-243
Instant OFF potential	-471	-587	-456	-395	-485	-495	-476
Potential shift	-275	-341	-235	-122	-250	-292	-233

The test procedure involves installing rebar connections and anodes within designated trial areas (1-2 m² each). Prior to energising the system, the natural potential of the embedded steel is measured at the concrete surface by external potential mapping using a copper/copper sulphate reference electrode. After the system is energised by a temporary power supply unit, the instant-off potential is recorded at the same locations after approximately 2 hours of polarisation, and the potential shift is calculated accordingly. An initial potential shift of around 100mV, within a range of 50mV to 250mV after two hours of energising, provides an indication that the current level impressed during the test is adequate to meet the protection criteria over the system's lifetime [3].

Determining the accurate current density ensures the design meets protection criteria, avoids over- or under-design, optimises anode spacing, and confirms long-term protection while minimising costs.

Most ICCP systems for concrete structures in Australia use Mixed Metal Oxide (MMO) titanium ribbon mesh and discrete anodes. The key design factors include:

- Verifying continuity of the embedded steel across the bridge, which may affect the number and size of protection zones.
- Assessing the condition of previously repaired areas, which can influence system performance. In most cases, old repairs need to be removed as part of the repair and ICCP system construction,
- Zoning the ICCP system based on current requirements and varying exposure conditions,
- Selecting appropriate methods for anode encapsulation in tidal and splash zones,
- Determining optimal reference electrode locations for system monitoring based on standard requirements [3], and
- Choosing a control system that ensures efficient operation and minimises maintenance costs.

The design of ICCP systems is well-established, with industry standards and guidelines supporting the development of robust designs that meet protection criteria.

For SACP systems, it is uncommon to conduct a current injection test to determine the long-term current density requirement. This is primarily because the initial potential shift for galvanic anodes is typically quite high; however, this potential shift could decrease rapidly over a relatively short period (1-2 months), after which the current stabilises at a consistent level.

For typical sacrificial anode design calculations, the mass of zinc required is determined based on the steel surface area using the following formula:

$$Mass = \frac{Z \times I \times T}{D \times U} \tag{1}$$

Where:

Z = Theoretical anode consumption rate
I = Current density required
T = Design life of the system (years)
D = Anode current efficiency factor
U = Anode utilization factor

Once the mass (weight of zinc) is calculated, and the weight of each anode is known, the number and spacing of anodes can be determined.

A key design challenge SACP systems in reinforced concrete structures is the substantial amount of zinc required to deliver the typical current density needed to meet protection criteria. As both the steel surface area and required current density increase, the demand for zinc scales accordingly. While embedding large quantities of zinc anodes is feasible in applications such as concrete overlays or jackets, it becomes structurally impractical when anodes must be embedded in drilled holes within the concrete. This method would require extensive concrete removal, requiring structural integrity assessment prior to embarking on the SACP installation.

The hybrid anode system consists of two phases: an initial impressed current phase (Stage 1) followed by a galvanic phase (Stage 2). In Stage 1, the hybrid anode system, specifically Type 1, operates by applying an impressed current through a temporary power source. The design concept is that the anodes are designed with sufficient charge capacity to deliver a minimum of 50 kC of charge per square meter of steel surface (approximately 14 Amp-hours per square meter). Additionally, the anodes must retain enough charge capacity to sustain a suitable current density during the galvanic phase.

In battery-based hybrid systems (Type 2), recommended charge levels of 50, 75, and 100 kC/m² are selected based on the chloride concentration in the concrete. Higher charge levels require larger batteries and bigger anodes. Once the impressed current phase is completed and the battery is depleted, the zinc anode takes over to deliver the maintenance current.

The aim of this paper is not to evaluate the theoretical assumptions regarding the efficiency of ICCP, SACP, or HACP systems. Instead, it focuses on assessing the actual performance of these systems in accordance with the relevant Australian standards for cathodic protection in concrete structures. Furthermore, this paper explores the reasons why certain technologies may fall short in delivering the required corrosion protection as specified by these standards.

5 Performance Results

The systems analysed in this paper include 10 ICCP systems with an average operational period of 7.5 years, 4 HACP systems operating for 3 years, and 7 SACP systems operating for an average of 4 years. The assessment is based on the most recent 2024 performance monitoring reports, evaluated in accordance with Australian Standard AS 2832.5-2008 [3].

Performance evaluation for each system was conducted against the protection criteria outlined in the standard. It is important to highlight that the data presented in this paper only includes the 24-hour decay data; however, the performance percentages are based on all the protection criteria specified in the applicable standard. The data summarises the percentage of reference electrodes in each system that meet (for ICCP systems) or meet/approach the protection criteria (for SACP and HACP systems). Approaching criteria is achieving 24h decay greater than 80mV.

The following table presents the system type, the percentage of reference electrodes meeting the criteria for ICCP systems, and the percentage of reference electrodes meeting or approaching the criteria for HACP and SACP systems, along with the combined average performance for each technology.

For the ICCP system, performance data from the latest 2024 assessment indicated that 87.50% of the reference electrodes met the protection criteria. Adjustments are carried out twice per year for each structure to account for changes in current demand, ensuring continued effective protection.

Our observations from continuous monitoring of ICCP systems indicate that the challenges in achieving 100% compliance with protection criteria are primarily linked to design factors, rather than limitations of the technology itself. Most ICCP performance issues stem from suboptimal design, then improper application/installation, and to some extent inefficient monitoring, rather than the system's inability to provide effective corrosion protection when above risks are mitigated. ICCP systems generally demonstrate compliance with Australian standards for protection criteria. Even in case of the 12.5% of the structures for which the full protection criteria have not been achieved, the ICCP system would provide some levels of protection (less than 100%) depending on the observed decay data.

Table 2. Performance assessment

No.	System	Number of RE	Meeting Criteria in accordance to AS 2832.5 (%)	Average
1	ICCP	55	74	**87.50%**
2		45	87	
3		49	91	
4		60	100	
5		58	97	
6		35	86	
7		52	74.5	
8		43	87.5	
9		24	100	
10		58	78	
Meeting or Approaching Criteria (%)				
11	HACP type 1	58	0	**0%**
12		79	0	
13	HACP type 2	10	0	**25%**
14		8	50	
15	SACP type 1	24	0	**0%**
16		8	0	
17	SACP type 2	9	44.4	**33%**
18		6	50	
19		26	69.2	
20		18	0	
21		4	0	

Table 3. Typical data from an ICCP system after 7 years of operation

Ref	**ON**	**IO**	**IR**	**24h OFF**	**24h Decay**
Ag/AgCl	mV	mV	mV	mV	mV
1	-750	-670	-80	-596	74
2	-495	-417	-78	-286	131
3	-746	-496	-250	-280	216
4	-507	-453	-54	-349	104
5	-584	-501	-83	-379	122
6	-442	-413	-29	-266	147
7	-716	-498	-218	-328	170
8	-778	-542	-236	-221	321

Key insights from system performance monitoring include:

- **Concrete Resistivity**: In a few circuits within one of the 10 systems, high concrete resistivity negatively affected performance. Although the system was designed based on a current density of 20 mA/m² of steel surface, elevated concrete resistivity increased the circuit voltage. Once the voltage exceeded 8V, the system's current delivery was restricted, preventing the protection criteria from being met. This issue could be fully resolved during the design stage by placing anodes closer to the rebar and with reduced spacing in high resistivity environments [18],
- **Design:** Design risks include, but are not limited to:
    - Insufficient system capacity during the design phase has led to under-protection in one circuit within one of the 10 systems. This circuit was

constructed with less than 50% capacity of the required design current, resulting in insufficient current to provide full protection,
    - In another case, the ICCP design did not cater for the changes in exposure conditions along the bridge which required separate zoning at different bridge spans, in addition to the traditional different vertical zones in the submerged, tidal, splash and atmospheric areas.
- **Installation:** For a few ICCP systems, the MMO titanium ribbon mesh was installed in the slot orientated vertically relative to the concrete surface which reduced the cover to the anode.
- **Monitoring:** The Australian Standard 2832.5 [3] requires at least functional checks at 3-month intervals (monthly in the first year of operation), performance assessment at 6-month intervals (3 month in the first year of operation), and system review at a maximum interval of 12 months. These are to be strictly followed to avoid monitoring risks.

Data from seven SACP systems, utilising two different types of galvanic anodes from separate manufacturers, were analysed. These anodes are the mostly used in Australia. Type 1 SACP uses anodes encapsulated by injected grout in drilled holes, while type 2 SACP employs anodes pre-encapsulated with grout by the manufacturer.

Of the seven systems, four exhibited poor performance, while the remaining three provided varying levels of protection, with compliance rates of 44.4%, 50%, and 69.2%.

The systems achieving 44.4% and 50% compliance were designed with relatively high current densities for SACP systems (7mA/m² of steel surface area) and featured anodes located in tidal/splash zones. Designing SACP with higher current density requires embedding more anodes within the concrete and spacing them closer together. This can be more easily achieved when large-scale repairs are conducted, allowing anodes to be installed alongside the patch repair work. It is essential to use low-resistivity mortar for patch repairs to ensure proper functionality of the SACP anodes.

The system with 69.2% compliance utilised in 4 out of 6 circuits, large zinc anodes embedded in overlays and concrete jackets. For those 4 circuits, 100% protection was achieved in accordance with the applicable standard after 3 years of system operation.

Two of the systems that failed to provide protection utilised Type 1 anodes, while the other two systems employed Type 2 anodes.

Below is typical performance data for SACP type 1 and SACP type 2 systems.

Table 4. SACP type 2 after 4 years of operation

Ref	ON	IO	IR	24h OFF	24h Decay
Ag/AgCl	mV	mV	mV	mV	mV
1	-359	-354	-5	-283	71
2	-450	-447	-3	-358	89
3	-400	-395	-5	-295	100
4	-262	-258	-4	-238	20
5	-271	-268	-3	-243	25
6	-281	-277	-4	-207	70
7	-385	-382	-3	-280	102
8	-292	-289	-3	-258	31
9	-400	-398	-2	-304	94

Table 5. SACP type 2 after 6 years of operation

Ref	ON	IO	IR	24h OFF	24h Decay
Ag/AgCl	mV	mV	mV	mV	mV
1	-470	-465	-5	-445	20
2	-445	-437	-8	-415	22
3	-441	-439	-2	-414	25
4	-470	-464	-6	-447	17

Table 6. SACP type 1 after 7 years of operation

Ref	ON	IO	IR	24h OFF	24h Decay
Ag/AgCl	mV	mV	mV	mV	mV
1	-280	-280	0	-273	7
2	-247	-247	0	-245	2
3	-238	-238	0	-234	4
4	-357	-355	-2	-341	14
5	-220	-200	-20	-196	4
6	-240	-240	0	-238	2

Key technical insights from the analysis are as follows:

- **Concrete Resistivity:** Concrete resistivity is a very critical factor in the performance of galvanic systems. Galvanic anodes installed in atmospheric environment such as headstocks in bridges (mostly concrete with relatively low chloride content and high resistivity) exhibited negligible performance. Installation of SACP systems in concrete with resistivity greater than 50 KΩ.cm must be avoided to avoid this risk.
- **Moisture Sensitivity:** Galvanic anodes perform better in wet conditions in tidal zones because moisture enhances the conductivity of the surrounding mortar. Systems located in tidal and splash zones provide higher protection levels compared to those in atmospheric environments, where low moisture content reduced effectiveness. In this regard, installation of SACP system in the submerged marine environment does not come with the abovementioned resistivity risk and facilitates installation of galvanic anodes in water. Zinc anode installed in water for the protection of the immersed sections of reinforced concrete piles provides 100% protection in accordance with the applicable standard [3].

- **Anode Types:** Anodes with manufacturer-installed grout encapsulation generally outperformed those encapsulated with injected grout in drilled holes. The consistency and quality of the pre-installed encapsulation may have contributed to more reliable performance. However, initial trials showed that the use of zinc anodes with encapsulated grout in wet areas may result in electrochemical byproducts leaching out to the concrete surface.

This paper evaluates four hybrid anode systems. Two type 1 HACP systems, where the impressed current phase is powered by an external power supply, and two type 2 HACP systems, where the impressed current phase is powered by hybrid anodes with an embedded battery inside the anode to provide current during the impressed current phase.

For the type 1 hybrid anode systems, data collected after three years of operation across two large installations revealed low to negligible performance for all reference electrodes and minimal current delivery during the galvanic phase. Although the exact cause of this level of underperformance remains unclear, it is likely that the zinc anodes had substantially reduced capacity following the impressed current phase. Potential contributing factors may include the formation of corrosion products around the anode during the brief impressed current phase, which could have significantly reduced current delivery during the galvanic phase.

Table 7. (HACP type 1) typical data after 3 years operation

Ref	**ON**	**IO**	**IR**	**24hOFF**	**24h Decay**
Ag/AgCl	mV	mV	mV	mV	mV
C1	-325	-325	0	-324	1
C2	-328	-328	0	-324	4
C3	-160	-160	0	-154	6
C4	-651	-651	0	-648	3
P1	-494	-494	0	-492	2
P2	-379	-379	0	-378	1
P3	-427	-427	0	-423	4
P4	-265	-264	-1	-264	0

In contrast, the hybrid anode system type 2 with a battery embedded in the anode, designed to power the initial impressed current phase, produced substantially better results for one system and poor results for another system. This first system provided protection in accordance with the protection criteria as outlined in the Australian standard for the first two years. However, in the third year, the protection levels decreased to 50%, likely due to the system automatically transitioning to galvanic mode. Ongoing monitoring is required to verify future performance. The anodes in this system were embedded within the concrete cover, which was exposed to a high-chloride environment and moisture. In this system, large anodes were utilised, including a sizeable, embedded battery to supply current during the impressed current phase.

For the second system type 2 HACP, smaller size anode was installed in drilled holes in atmospheric areas of a bridge. The data appears to be consistent with the SACP performance in atmospheric areas.

The substantial variability of the performance of both type 2 HACP systems in concrete suggests that the system design and concrete resistivity plays a major role in system performance.

Table 8. (HACP type 2) data after 3 years of operation

Ref	**ON**	**IO**	**IR**	**24h OFF**	**24h Decay**
Ag/AgCl	mV	mV	mV	mV	mV
R1	-415	-410	-5	-283	127
R2	-429	-426	-3	-307	119
R3	-318	-322	4	-241	81
R4	-377	-383	6	-292	91
R5	-347	-342	-5	-281	61
R6	-345	-343	-2	-282	61
R7	-322	-318	-4	-246	72
R8	-341	-337	-4	-275	62

Table 9. (HACP type 2) data after 3 years of operation

Ref	**ON**	**IO**	**IR**	**24hOFF**	**24h Decay**
Ag/AgCl	mV	mV	mV	mV	mV
1	-93	-92	-1	-92	0
2	-166	-166	0	-164	2
3	-261	-260	-1	-258	2
4	-127	-126	-1	-107	19
5	-200	-199	-1	-180	19
6	-353	-352	-1	-347	5

6 Current Requirements to Maintain Protection

One of the key factors in selecting an electrochemical protection system for corrosion control is evaluating whether the system's anode can supply the required cathodic protection current throughout its design life. Additionally, it is important to consider data on potential changes in current requirements over the system's lifespan, whether they increase or decrease.

The factors influencing the required current density for a corrosion protection system in a reinforced concrete structure include:

- **Corrosion Activity of Embedded Steel:** This is affected by chloride concentration, typically assessed through chloride analysis and potential mapping. For example, steel with more negative potentials (e.g., more negative than -400 mV with regards to $Cu/CuSO_4$ reference electrode) requires a higher cathodic protection current than steel with potentials closer to -200 mV to the same reference electrode.
- **Surface Area of Steel:** The total steel surface area requiring protection directly impacts the required current. A larger surface area of steel demands higher current density to provide effective protection.

- **Concrete Resistivity:** High concrete resistivity does not necessarily indicate lower corrosion activity, as rebar corrosion can still occur in such conditions. Cathodic protection design must account for this, and in areas with high resistivity, closer anode placement and reduced spacing between the anode and rebar may be necessary to ensure effective protection [18].

An assessment of the ongoing current demand for the 10 ICCP systems assessed in this paper was conducted, examining both the current requirements at the commissioning phase and after several years of operation. The table below presents data on the initial current requirements during commissioning and the current requirements after an average of 7.5 years of operation. It also shows the percentage of current decrease or increase necessary to maintain protection, in accordance with the applicable standards.

Table 10. Current requirements over 7.5 years for ICCP systems

No	System ON	Years	Initial mA	2024 mA	% Change	Average
1	2012	12	18083	12086	67%	70%
2	2017	7	12140	11119	92%	
3	2017	7	5640	3271	58%	
4	2017	7	7800	3002	38%	
5	2016	8	12600	9440	75%	
6	2015	9	4000	2466	62%	
7	2020	4	4100	3130	76%	
8	2018	6	1810	1621	90%	
9	2017	7	13230	14520	110%	133%
10	2016	8	2690	4220	157%	

The initial current values in (mA) shown in table 10 were sourced from the commissioning reports of these systems. After commissioning, which followed the relevant standard [3], each system was set to operate at the specified current to meet the protection criteria.

The 2024 current values in (mA) come from the most recent monitoring reports conducted in 2024. During these monitoring activities, the operating currents were determined based on tests and adjustments in accordance with the applicable standards. For systems 1–8, the average current required to maintain protection after approximately 7.5 years is 70% of the initial current, while for systems 9 and 10, the average current required to maintain protection is 133% of the initial current.

The purpose of this data is to evaluate the current levels necessary to maintain protection during the system operation. It will be used to assess the reason of the different protection levels provided by ICCP, HACP, and SACP systems discussed in this paper.

The ICCP systems, mainly utilising MMO coated titanium anodes, successfully deliver current without significant restrictions under normal conditions. However, in environments with high concrete resistivity, the system may face limitations when the voltage exceeds 8V, resulting in restricted current output. This issue can be identified during the design stage and the risk of current restriction can be eliminated.

For type 1 HACP systems, the level of corrosion protection was found to be 0% (nil) based on the applicable standard [3] for 2 relatively large HACP systems as reported in tables 2 and 7. A possible explanation of the primary reason for the poor performance of these systems is as follows:

The HACP concept is based on the idea that embedded reinforcing steel can be passivated after a brief period of impressed current, typically delivering 50 kC of electrical charge. This represents around 38.6 days of ICCP operation at a current density of 15 mA/m² of steel surface area. After this period, it was assumed that a minimal maintenance current, provided by the embedded zinc anodes used in the impressed current phase, would be sufficient to maintain corrosion protection. However, data on the current requirements during ICCP operation, as presented in table 10, reveal significant flaws in this assumption. The data suggest that similar, slightly lower, or in some cases even higher current levels are required throughout the system's life to maintain adequate protection.

Although HACP systems can deliver ICCP-level current for the initial 38.6 days (at 15 mA/m²), the expectation that a substantially lower current of around 1–2 mA/m² can provide sustained protection for the remainder of the system's life is unsupported by the data.

The performance data from two large type 1 HACP systems presented in this paper clearly show that after the impressed current phase ends, the zinc anodes fail to provide ongoing protection. The brief impressed current phase had either minimal impact on the steel potential or any shift in potentials during the impressed current phase has faded away after switching to the galvanic phase (steel has depolarised after the phase 1). The 24 off-potentials from the embedded Silver/Silver Chloride reference electrodes were in the same range of the natural potential of the reinforcement before any cathodic protection was applied, confirming that the short impressed current phase had little effect on long-term steel potential.

During the galvanic phase, the steel potential remains largely unchanged, as the zinc anodes were unable to supply the required maintenance current to influence the rebar potential.

Type 2 HACP systems offer full protection during the initial impressed current phase, as anticipated, but show a predictable decline in performance once they enter the galvanic phase. The main distinction between HACP Type 1 and Type 2 is that in Type 2, the zinc anode is not affected by the initial impressed current phase. In Type 1, corrosion products may accumulate around the zinc anode during this phase, potentially blocking the anode's ability to deliver full current during the galvanic phase. In contrast, Type 2 systems rely on a battery for the impressed current phase (the zinc is not consumed during this phase), and once this phase is complete, the zinc anode functions purely as a galvanic anode.

The data presented in table 2 indicates that SACP systems are effective in low-resistivity environments such as overlays or jackets but face significant limitations when embedded in drilled holes in concrete bridge elements for global protection. The large amount of zinc required for sustained protection, combined with the inability of these anodes to deliver sufficient cathodic protection current in moderate to high-resistivity concrete and highly corrosive environments, makes them less effective for long-term corrosion protection in marine environments, particularly for global bridge protection, as demonstrated by the data. In contrast to the performance of galvanic anodes (primarily zinc) embedded in concrete, the use of galvanic bulk anodes in submerged marine environments, such as salt and brackish water, has consistently demonstrated 100% performance in protecting the immersed sections of piles, in accordance with the applicable standard [3].

7 Conclusions

In conclusion, ensuring durable corrosion protection for reinforced concrete structures requires selecting systems that consistently deliver the necessary cathodic protection current density in accordance with established standards to meet protection requirements.

The findings in this paper indicate that SACP systems may not consistently meet these protection criteria. However, under favourable conditions, they can still offer varying degrees of protection, making them suitable for specific applications.

SACP systems are particularly well-suited for certain concrete structures where ICCP systems may not be practical. These applications include structures with a limited design life, pre or post tensioned elements, those with poor electrical continuity, reinforced concrete elements in residential or commercial buildings where ongoing ICCP maintenance would be challenging, and small or remote bridges that lack access to mains power.

In such scenarios, SACP can serve as a practical alternative. With thoughtful design, SACP systems can be optimised to enhance the performance of galvanic anodes, maximising their protective capabilities even within the inherent limitations of the technology.

The data on HACP Type 1 highlights significant limitations in its ability to deliver effective long-term performance, whereas HACP Type 2 presents mixed outcomes.

These findings raise important questions about the overall effectiveness of hybrid anodes as a cathodic protection technology which is based on classic definition of cathodic polarisation of all cathodes to the potential of most active or anodic sites. This is particularly important as alternative criterion of corrosion rate measurement is not as straightforward and is challenging to implement for infrastructure assets.

While the brief impressed current phase in HACP systems may temporarily influence steel potential, this impact, equivalent to just one month of ICCP system operation, offers minimal benefit over the lifetime of the structure. Beyond this short phase, the system's performance relies entirely on the galvanic anode for the remainder of its operational life.

The assumption that a brief impressed current phase, followed by a much lower galvanic current, can satisfy the potential criteria is fundamentally flawed, as clearly demonstrated by the data presented in this paper. If galvanic protection is the chosen strategy, it would be more practical and cost-effective to design a dedicated galvanic anode system without the added complexity and cost associated with achieving short-term reinforcement passivation through HACP Type 1.

For HACP Type 2, the installation process is comparable to that of a standard SACP system, with the only significant difference being the larger hybrid anode to accommodate the built-in battery. This similarity simplifies the adoption of HACP Type 2 for practitioners familiar with SACP systems, which is a positive aspect. However, the initial passivation phase of HACP Type 2, while potentially beneficial in the short term, does not lead to a meaningful reduction in long-term current demand. The system's performance, much like traditional SACP, largely depends on the quantity of zinc and the environmental conditions surrounding the anode, rather than on the brief passivation phase.

From a cost-benefit perspective, HACP Type 2 may offer a slight advantage, though it comes with a marginal increase in cost. It's important to note that, for both HACP Type 2 and SACP Type 2, the design life and ability to meet protection criteria are fairly similar. Neither system can match the performance or versatility of the impressed current systems, which remains the only cathodic protection technology for delivering extended durability and active protection.

The data in this paper underscores the reliability of ICCP systems when properly designed, installed, and monitored. ICCP provides a durable solution for corrosion protection in reinforced concrete structures, consistently meeting the potential criteria for cathodic protection, particularly in aggressive marine environments where other systems may struggle to achieve the same level of performance.

Even though ICCP is a proven solution for demanding conditions, it may not be suitable for every structure. Thorough engineering and electrochemical assessment are essential to identify the most appropriate corrosion protection strategy for each unique case.

In conclusion, this paper offers an objective comparison of various corrosion protection systems based on real operational data. Asset owners and corrosion engineers should carefully assess the specific requirements of each structure to determine the most effective and sustainable corrosion protection solution.

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