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ORIGINAL ARTICLE

Investigation of residual protection of a 55 years old marine structure after 20 years subject to impressed current cathodic protection

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Abstract It has been reported that structures to which impressed current cathodic protection (ICCP) has been applied for a long period have displayed evidence of residual protection when ICCP has been halted, ranging from several days up to significantly longer periods. To study this phenomenon this paper reports the de-activation of a 20 years old ICCP system installed on a 55 years old wharf structure. The ICCP was de-activated for 84 days and the reinforcing steel potentials at locations on the front pile cap and front wall were monitored via the existing installed reference electrodes (RE). The results showed that all the RE installed in the structure initially demonstrated a positive shift in potential, with 61% maintaining a positive trend over the entire trial period.

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1 Introduction

The durability of marine infrastructure (in particular wharfs and docks) is of paramount importance in ensuring these assets achieve their specified design life. The primary deterioration mechanism for these structures is corrosion of the reinforcement, due to chloride ingress [1]. In uncontaminated concrete reinforcing steel is passive due to the high pH generating a passive layer on the steel surface which prevents corrosion [1, 2]. However, when chlorides reach a critical concentration at the rebar the passive layer can be broken down and corrosion initiated [3, 4]. This corrosion can subsequently lead to concrete cracking, concrete spalling and compromise the structural integrity of the infrastructure. The annual global cost of the repair and maintenance of reinforced concrete infrastructure is understood to be in the billions of dollars [5].

Whilst a range of repair methods can be employed including patch repair and electrochemical treatment [6] historically the most common method for aggressive marine environments is Impressed Current Cathodic Protection (ICCP) [7–11]. ICCP protects reinforcement by the application of a direct current which polarises the steel to more negative values. This re-establishes passivity on the steel rebars [12–14]. In addition to this primary mechanism a number of secondary mechanisms also exist which contribute to the long term protection of the steel [9]. These include the production of hydroxyl ions at the rebar surface, the repulsion of chloride ions from the region around the rebar and the consumption of oxygen. These effects have been reported to provide a period of residual protection following the halting of ICCP.

Residual protection has been observed on a number of structures where ICCP systems have been de-activated [15, 16, 16–18, 18]. A study in the United Kingdom found that the steel remained passive for three years following decommissioning of the ICCP system [16, 18]. A study in Australia on two wharf structures also reported evidence of residual protection when the ICCP systems were de-activated for a three month period [17]. While similar observations were also observed on a another ICCP system in Australia applied to a wharf in a different state, which would be subject to different environmental conditions [18]. However, on some structures only short term residual protection has been observed, with corrosion re-initiating being reported within three days [17]. A number of factors have been suggested as determining if a structure will display residual protection and the duration of the residual protection. Factors identified include charge density, total charge passed, duration of operation of the ICCP system, the design of the system, tidal cycles (internal relative humidity (RH) and moisture), chloride content and electrochemistry of the pore water. As many ICCP systems are approaching the end of their design lives an understanding of these mechanisms can provide vital information for engineers to determine the optimum asset management strategy and the residual service life of a structure. Additionally, it is anticipated to provide insights into the most effective asset management protocol to extend service life and minimise costs. This investigation reports a trial on a 55 years old reinforced concrete wharf, where the ICCP system which had been operating for 20 years, was de-activated for a period of three months. The wharf was constructed in 1969 in southern Australia, the ICCP system was installed in 1999, and the trial was conducted over the Christmas/New Year period 2018–2019 in agreement with the Port Authority.

To date, few studies have been conducted to assess the performance of ICCP systems with respect to residual protection of reinforced concrete structures. The novelty of this study is in providing a systematic analysis of the residual protection of an operating port facility, where the ICCP (and water anodes) have been de-activated for a 3 month period. The monitoring data enables the study of specific elements, wall and pile caps, in three distinct exposure zones, tidal, splash and atmospheric. This enables an analysis of the differences in element type and most significantly in varied environmental exposure zones where the conditions initiating the initial corrosion and the re-initiation of corrosion post ICCP are expected to vary significantly. The data provides a clearer understanding of the behaviour of these elements and exposure categories on residual protection, which has the potential to improve asset management strategies as well as further the understanding of ICCP and secondary effects of the ICCP on reinforced concrete structures.

2 Materials and methods

The study was conducted at the Port of Portland, which is located in the state of Victoria, Australia. Portland is located on the southern coast of Victoria, Australia and is subject to an aggressive marine environment. The study was undertaken on Berth 6, which was constructed in 1969 as part of the expansion of the Port, Fig. 1. This is the same location as an earlier study on the Smelter Berth [19] at the Port of Portland, which was constructed in 1982 with the ICCP system installed in stages between 2005 and 2012. In comparison to the Smelter Berth study the current study is undertaken on a structure 13 older and with ICCP applied for 10 years longer (a total of 20 years).

Berth 6 is adjacent to Berth 5 (the subject of a previous study [19]). The steel in concrete ICCP system was installed on Berth 6 in 1999. Annual survey reports from 2008, 2014, 2015 and 2018 and the initial commissioning reports were reviewed to provide details of the ICCP system and the operational parameters including; system design, anode type, anode layout, reference electrode type and location, applied current density and charge passed. Based on the reports it was determined that the ICCP system was

Fig. 1 Port of Portland

designed in-line with early draft revisions of ISO 12696 [20]:

- Provide a maximum current density of 20 mA/m^2 of steel reinforcement surface area.
- Not exceed the anode output rating of 110 mA/m^2 of the anode surface area.
- Operate on a working voltage between the reinforcing steel and the anodes of less than 5 V in order to minimise the risk of pitting corrosion on the titanium conductor bar.

Analysis of the reports indicated the ICCP system consists of:

- Slotted mixed metal oxide (MMO) coated titanium ribbon anodes embedded in horizontal slots in the transverse pile headstock beams.
- Internal discrete MMO ceramic tubular anodes installed into horizontally drilled holes within the front curtain wall beam and,
- Silicon chromium iron anodes installed in vertical holes behind the rear wall and backfilled with metallurgical coke breeze to protect the rear retaining wall.

The slotted and internal discrete anodes are backfilled with a low resistivity cementitious grout. The internal concrete anodes have a venting system to enable gases generated by the anodic reaction to diffuse into the centre of the porous anodes and vent to the atmosphere via a network of nylon tubes. This was to enable the application of a high current density whilst preventing deterioration of the cementitious backfill.

The anodes are powered via a transformer rectifier (TR) unit situated in the electrical room at the east end of the dock. The system is divided into eight operating zones with eight separate AC/DC controllers within the primary TR unit, Fig. 2. The zones are defined as follows:

- Zone 1, reinforced concrete rear wall in the atmospheric and splash exposure zones. Current provided to soil anodes, a maximum output of 20 Amps.

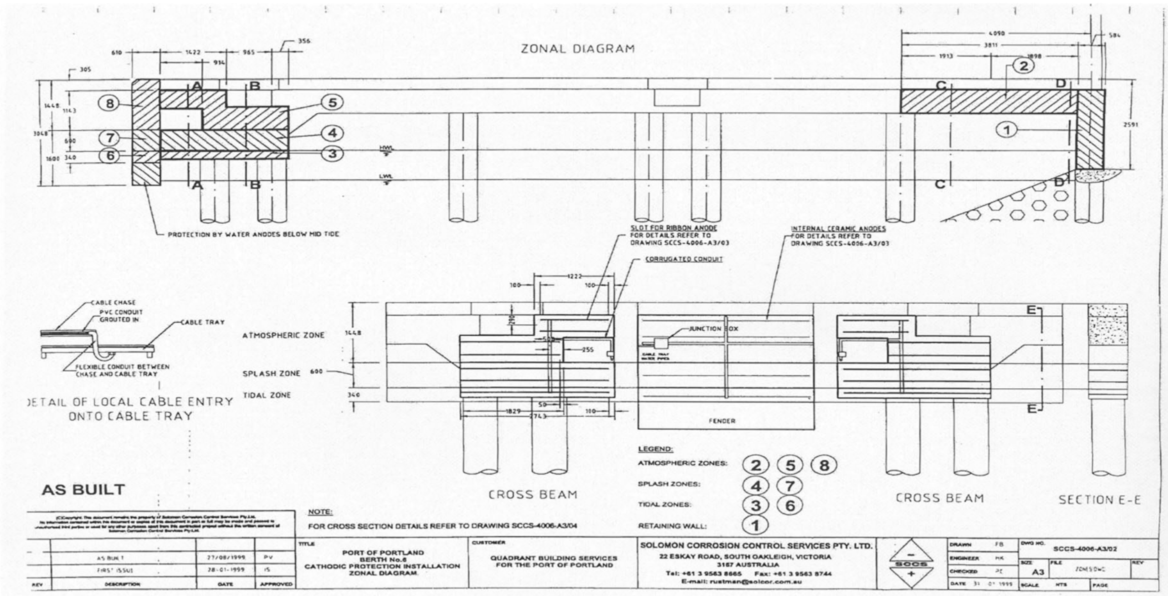


Fig. 2 As built drawing: Operating Zones Berth 6

- Zone 2, reinforced concrete rear transverse beam in the atmospheric exposure zone (Those parts of a concrete structure that are continuously exposed to the atmosphere) [20].
- Zone 3, reinforced concrete pile cap in the tidal exposure zone (The parts of the concrete structure that are submerged or exposed according to changing water levels or tides) [20].
- Zone 4, reinforced concrete pile cap in the splash exposure zone (The parts of the concrete structure above high water level which are wetted by wave or splash action) [20].
- Zone 5, reinforced concrete pile cap in the atmospheric exposure zone.
- Zone 6, reinforced concrete front wall (fender) in the tidal exposure zone.
- Zone 7, reinforced concrete front wall (fender) in the splash exposure zone.
- Zone 8, reinforced concrete front wall (fender) in the atmospheric exposure zone.

A total of 52 silver/silver chloride permanent reference electrodes (Ag/AgCl/0.5 M KCl) (RE) were embedded across the various reinforced concrete elements. Three are located in the rear wall (Zone 1), a further seven are located in the rear transverse beam (Zone 2). The remaining 42 RE are in Zones 3 to 8. These are distributed across the tidal, splash and atmospheric exposure zones of both the front pile cap and the front wall. The RE in Zone 1 and in Zone 2 were not operational at the time of the study. A data logger was employed to record the steel potential data for the 42 reference electrodes in Zones 3–6. The data for RE 25 displayed a potential which ranged between + 2000 and − 3000 mV. Based on the variation and magnitude it was determined that RE 25 was not operating correctly, and the data was excluded from the study. The fault with this reference is consistent with the ICCP monitoring reports which have also noted this reference as faulty.

The As Built drawings of the system and the operating zones are illustrated in Fig. 2. In addition to the system described above, a system of water anodes is installed to provide protection to the steel piles within Berth 6. The pile CP system is expected to provide a level of current to elements in Berth 6 which are submerged during tidal movements.

The concrete ICCP system was decommissioned for a total of 84 days. This was the maximum time agreed with the Port authority in order to minimise the possibility of adverse impact on the structure. In addition, the water anode system was de-activated for a 48-h period, commencing 2 h following the deactivation of the ICCP system. The water anode system was then re-activated. The potential of the steel protected by the concrete ICCP system was monitored at 5 s intervals over the initial 5 min following deactivation to record the instant-off data. Potential data was then recorded at 5 min intervals in the initial 48-h period when the water anodes were de-activated and then at one hour time intervals for the rest of the 84 day de-activation period. Monitoring of the system commenced on the 30th of November 2018 and the ICCP was re-activated on the 22nd of February 2019.

3 Results

The system is designed to operate in accordance with AS 2832.5 [21], which specifies protection based on fulfilling one of four criteria. These criteria are similar to those used in other standards, including ISO 12696:2016 [20].

A potential decay (The change in electrode potential with time, resulting from the interruption of the applied current) [20] over a maximum of 24 h of at least 100 mV from the instantaneous off potential (The electrode potential taken immediately after complete disruption of d.c. power (either impressed current or galvanic) to the system. The instantaneous off-potential is used as a close estimate of the IR drop-free polarized potential when there was current flow) [20]. This is known as the potential decay criterion.

1. 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. This is known as the extended potential decay criterion.
2. An instantaneous off potential more negative than − 720 mV with respect to a Ag/AgCl/0.5 M KCl reference electrode. This is known as the absolute potential criterion.
3. A fully depolarised potential, or a potential which is continuing to depolarise over 72 h after the ICCP system has been switched off which is consistently less negative than − 150 mV with respect to Ag/AgCl/0.5 M KCl reference electrode. This is known as the absolute passive criterion.
4. All potentials quoted in this paper are relative to Ag/AgCl/0.5 M KCl unless noted otherwise.

The ON potential (The potential, including resistance potential, of a polarized structure) [20], instant off potential, 24-h decay data, the steel potential at the conclusion of the de-activation period and the shift in potential over the 84 day deactivation period are given in Table 1. Decay plots for reference electrodes in the tidal, splash and atmospheric environmental zones for the front pile cap and for the front wall are given in Figs. 3, 4, 5, 6, 7, 8. These are presented in sets of reference electrodes corresponding to the environmental zones (tidal/splash/atmospheric) for either the front pile cap or front wall.

3.1 Results—ON potential

In most cases there is a clear differentiation between the ON potentials in the three distinct environmental zones.

- Tidal Zone. The tidal zone ON potentials vary from − 727 to − 323 mV in the front wall and from − 709 to − 209 mV for the front pile caps.
- Splash Zone. The ON potentials vary from − 557 to − 301 mV in the front wall and − 777 to − 423 mV in the front pile caps.
- Atmospheric zone. The ON values range from − 829 to − 204 mV in the front pile caps and − 821 to − 143 mV in the front wall.

The REs generally have the most negative values and those in the atmospheric the least negative. However, this not universally observed. In the tidal zone the ON potentials for both the pile caps and the wall are similar, however in the splash and atmospheric zones the potentials are generally more negative in the pile caps than the front wall. The piles caps are more exposed to the wave impact due to their location. This exposure would be expected to lead to lower concrete resistivity as well as higher rate of chloride ion ingress. Consequently, a higher rate of corrosion would be expected in this region requiring a greater current density leading to the more negative ON potentials observed. It is also hypothesised that the location of the different Zones (3–8) along the Berth may contribute to the differences in the potential observed. It is believed that due to local geographic factors certain Zones are more exposed to wave action both when a ship is and is not docked at the Berth.

In addition to the variation between Zones, the exact location of the RE within a given zone is not

Table 1 Location and potential data for reference electrodes (silver/silver chloride)

Ref	Zone	Location	ON potential (mV)	Instant OFF potential (mV)	24 Hour OFF potential (mV)	24 h decay (mV)	72 h decay (mV)	Final shift from on potential (mV)
1	3	T/FPC	− 343	− 295	− 185	110	121	150
2	4	S/FPC	− 456	− 319	− 176	143	170	198
3	5	A/FPC	− 209	− 203	− 111	92	112	124
4	6	T/FW	− 434	− 434	− 462	− 28	− 151	4
5	7	S/FW	− 354	− 345	− 280	65	64	83
6	8	A/FW	− 266	− 264	− 199	65	95	91
7	3	T/FPC	− 464	− 425	− 331	94	131	204
8	4	S/FPC	− 704	− 431	− 271	160	212	358
9	5	A/FPC	− 302	− 295	− 201	94	122	129
10	6	T/FW	− 689	− 677	− 641	36	− 47	80
11	7	S/FW	− 505	− 460	− 378	82	75	120
12	8	A/FW	− 465	− 447	− 238	209	258	350
13	3	T/FPC	− 711	− 669	− 593	76	106	254
14	4	S/FPC	− 681	− 563	− 383	180	203	268
15	5	A/FPC	− 835	− 670	− 403	267	366	414
16	6	T/FW	− 595	− 595	− 615	− 20	− 114	56
17	7	S/FW	− 567	− 467	− 280	187	175	209
18	8	A/FW	− 822	− 794	− 681	113	196	446
19	3	T/FPC	− 210	− 210	− 205	5	9	18
20	4	S/FPC	− 480	− 476	− 422	54	52	197
21	5	A/FPC	− 414	− 397	− 268	129	145	186
22	6	T/FW	− 730	− 707	− 490	217	335	486
23	7	S/FW	− 375	− 358	− 168	190	243	296
24	8	A/FW	− 146	− 148	− 145	3	10	21
25	3	T/FPC	N/A	N/A	N/A	N/A	N/A	N/A
26	4	S/FPC	− 774	− 691	− 521	170	264	453
27	5	A/FPC	− 430	− 379	− 239	140	143	172
28	6	T/FW	− 331	− 316	− 196	120	117	124
29	7	S/FW	− 438	− 425	− 350	75	44	102
30	8	A/FW	− 156	− 156	− 136	20	31	44
31	3	T/FPC	− 611	− 389	− 163	226	61	47
32	4	S/FPC	− 514	− 399	− 293	106	112	154
33	5	A/FPC	− 431	− 372	− 214	158	150	158
34	6	T/FW	− 499	− 478	− 386	92	57	115
35	7	S/FW	− 360	− 356	− 302	54	160	213
36	8	A/FW	− 317	− 322	− 272	50	42	59
37	3	T/FPC	− 361	− 354	− 341	13	− 43	52
38	4	S/FPC	− 427	− 381	− 320	61	56	99
39	5	A/FPC	− 316	− 302	− 206	96	102	113
40	6	T/FW	− 615	− 613	− 595	18	− 19	135
41	7	S/FW	− 302	− 292	− 236	56	65	87
42	8	A/FW	− 144	− 144	− 115	29	36	42

T Tidal, *S* Splash, *A* Atmospheric, *FPC* Front Pile Cap, *FW* Front Wall

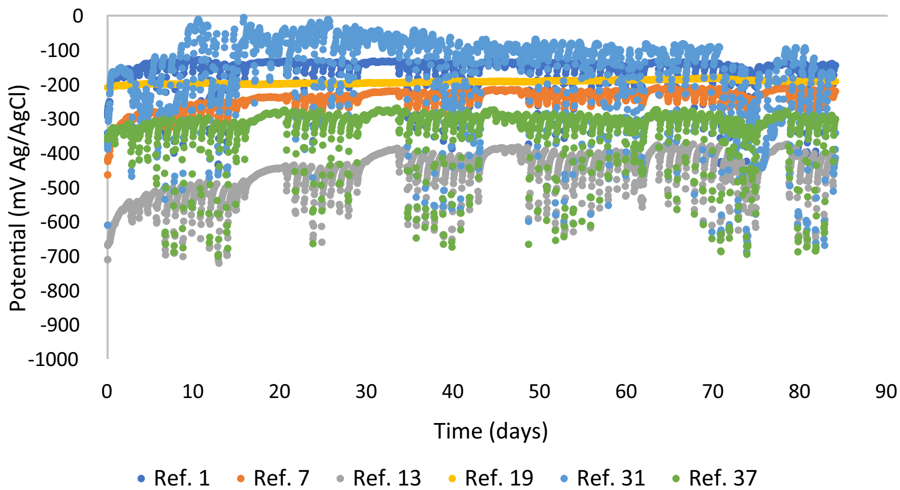


Fig. 3 Decay curves for Tidal Zone, Front Pile Caps

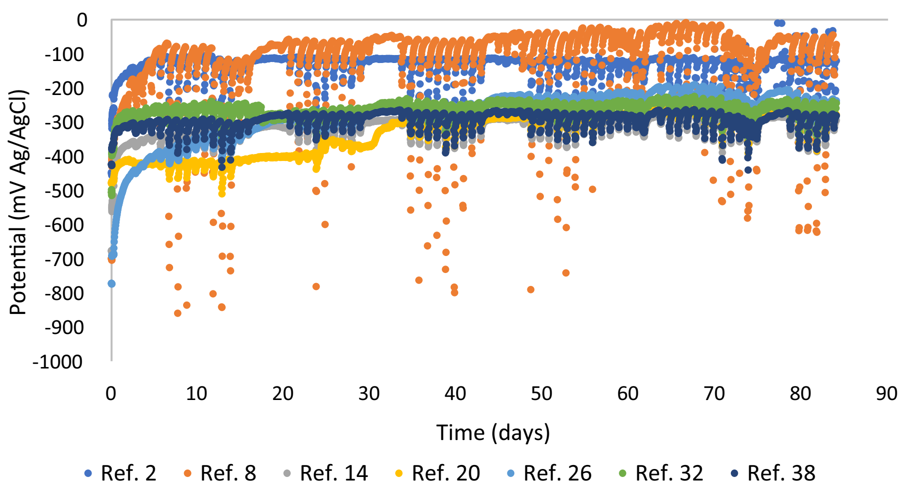


Fig. 4 Decay curves for Splash Zone, Front Pile Caps

provided in the documentation supplied. It is possible that all the REs within a zone are installed at different heights within the tidal, splash and atmospheric zones and in different orientations to the wave action. Hence, variability in the positioning of the RE may also be a factor contributing to the differences observed in the ON potentials as each location would be subject to different exposure condition and therefore have a different chloride contents and corrosion rates.

3.2 Results—potential decay

The tidal cycle can be observed on the majority of the REs located in the tidal and splash zones. The tidal cycle is also evident on a number of the REs in the atmospheric zone, Figs. 9 and 10. The active shift in potential associated with the tidal cycles is generally of the order of 50 mV, though this does increase significantly in some cycles. Potentials more negative than -800 mV are observed for REs in the tidal zone in the front wall and -700 mV for the front pile caps. These shifts in potential to more negative (active) values are consistent with those observed in previous studies and are attributed to the saturation of the concrete surface during tidal cycles, resulting in oxygen depletion and cathodic polarisation due to the slow rate of oxygen transport through water saturated capillaries in the cement matrix, rather than from the re-initiation of active corrosion [24].

In addition to the typical tidal cycle, all of the REs demonstrate a particular trend, where for several days there is a period of potential decay without the daily

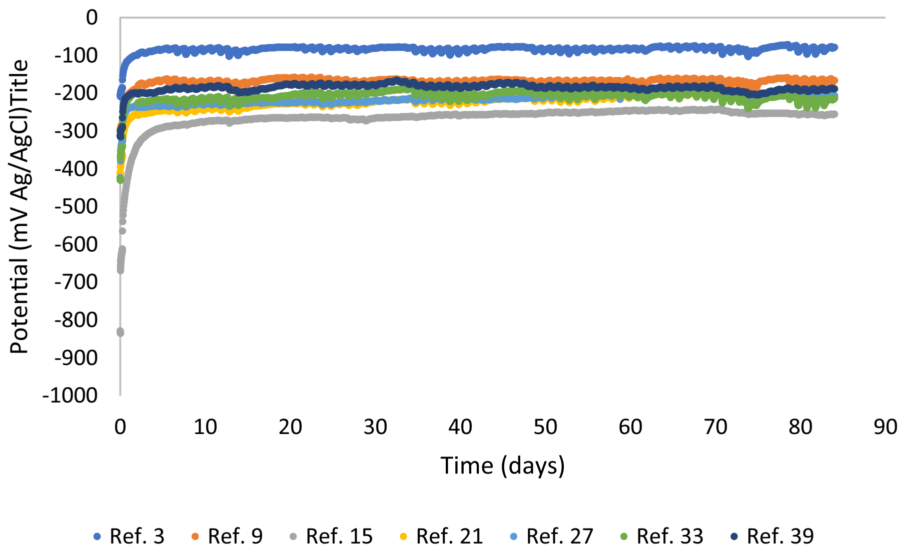


Fig. 5 Decay curves for Atmospheric Zone, Front Pile Caps

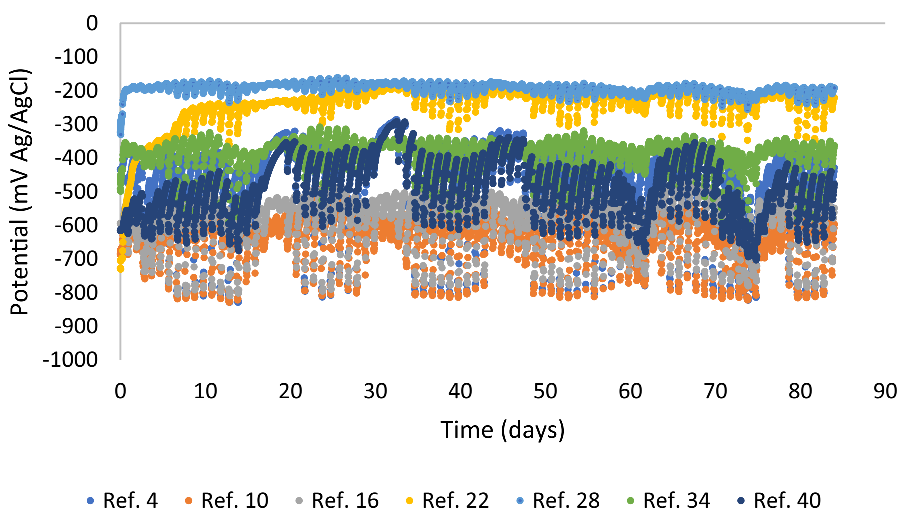


Fig. 6 Decay curves for Tidal Zone, Front Wall

repolarisation due to the tidal cycle. This trend can be observed on the RE in the tidal zones in Fig. 11. These periods typically occurred fortnightly, starting around day 15, with the mid-point of each event occurring approximately every 14 days. This trend was particularly apparent in the tidal and splash zones. The authors attribute this to neap tides which occur twice per lunar month. This is consistent with the frequency of the observed time interval between these events as can be observed in the variation in tide heights in Fig. 11. During a neap tide the relative position of the moon, earth and sun combine to mean that the high tide is lower than would otherwise be observed. This will result in the water at high tide not reaching most (sometimes none) of the tidal or splash zone RE locations and wave splash is much lower on the structure. Consequently, the potential decay will also be greater during the neap periods because there is not the daily repolarisation to more negative potentials due to water contact in the higher tidal periods. This corresponds exactly with the observations in the decay plots. All REs are understood from discussions with port personnel to have been installed at least above mid-tide level. The very bottom of zone 3 (tidal) for instance is well above mid-tide and REs here are well above the bottom edge of the beam. It is also expected that the installation of REs in the front beam in zone 6

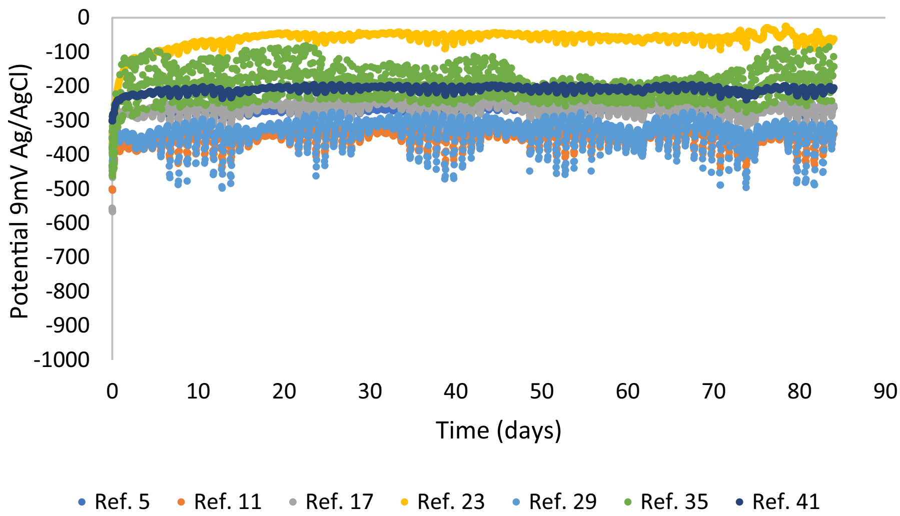


Fig. 7 Decay curves for Splash Zone, Front Wall

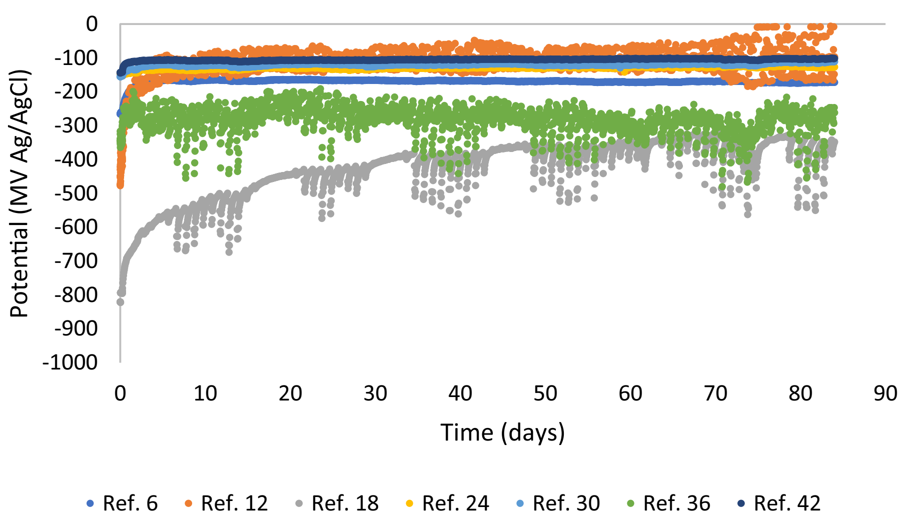


Fig. 8 Decay curves for Atmospheric Zone, Front Wall

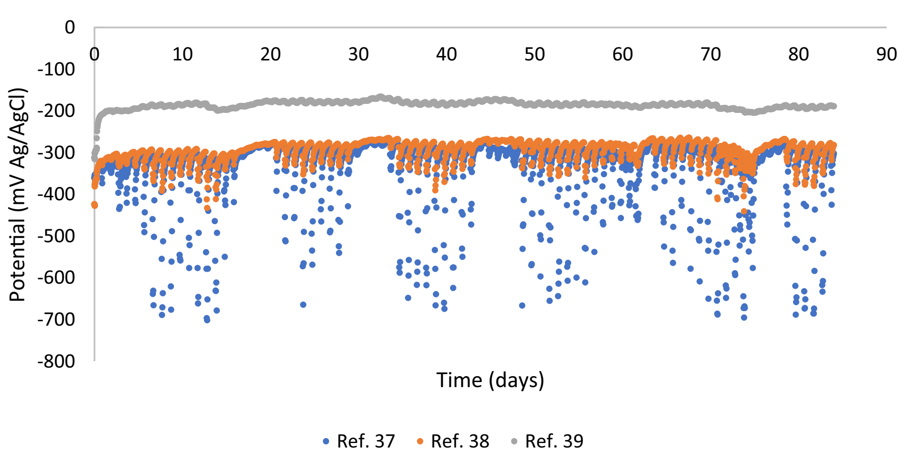


Fig. 9 Decay curves for reference electrode 37 (tidal, zone 3), reference electrode 38, (splash, zone 4) and reference electrode 39 (atmospheric, zone 5), Front Pile Caps

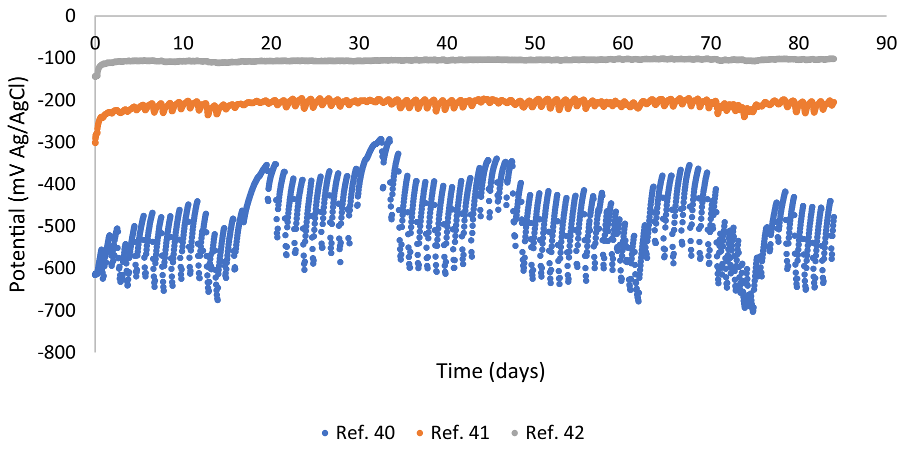


Fig. 10 Decay curves for reference electrode 40 (tidal, zone 6), reference electrode 41, (splash, zone 7) and reference electrode 42 (atmospheric, zone 8), Front Wall

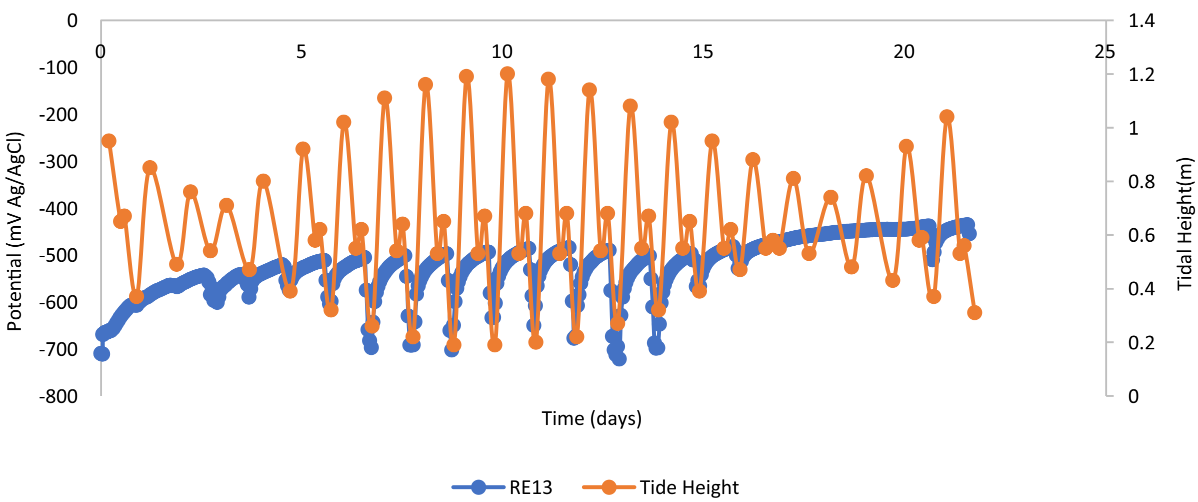


Fig. 11 Tidal cycle vs decay curve for reference electrode 13 (Tidal, Zone, Front Wall, Day 0 to Day 25

(tidal) would have been installed above mid-tide for practical and accessibility reasons.

4 Discussion

4.1 Discussion—depolarisation of REs

An analysis of the potential decay curves following deactivation of the ICCP system shows that 17 of the 41 RE satisfy the 24 h decay criterion, achieving at least 100 mV decay after 24 h. An additional five RE had a decay potential of greater than 90 mV after 24 h. Thus, just over half the RE satisfy or are close to satisfying this criterion. The distribution of the 17 RE that achieved the 100 mV decay within the zones is shown in Table 2 below and the depolarisation status of all REs after 24 h is shown in Fig. 12 below.

From Fig. 12 it can be seen that of the twenty-two RE that achieve 90 mV or greater this includes all seven in the front pile cap atmospheric zone and a total of fifteen out of twenty in the front pile caps but only seven out of twenty-one in the front wall.

It can also be seen that twelve out of the twenty-two RE are located in Zones 4 and 5. These Zones correspond to the central section of Berth 6. A similar number of RE in the tidal zones achieve the 24 h decay criterion for both the front wall and front pile cap but only four in the splash and atmospheric zones of the front wall achieve the 100 mV decay compared to twelve in the front pile caps. Meanwhile, two locations displayed a negative decay, Ref. 4 and Ref. 16. Both of

Table 2 Number of REs which achieved at least 90 mV depolarisation within 24 h of Instant Off

Zone	Number of REs achieving 100 mV decay in 24 h
Pile cap, tidal zone (zone 3)	2
	1*
Pile cap, splash zone (zone 4)	5
Pile cap, atmospheric zone (zone 5)	4
	3*
Front wall, tidal zone (zone 6)	2
	1*
Front wall, splash zone (zone 7)	2
Front wall, atmospheric zone (Zone 8)	2

*RE achieved 90 mV depolarisation within 24 h of Instant Off

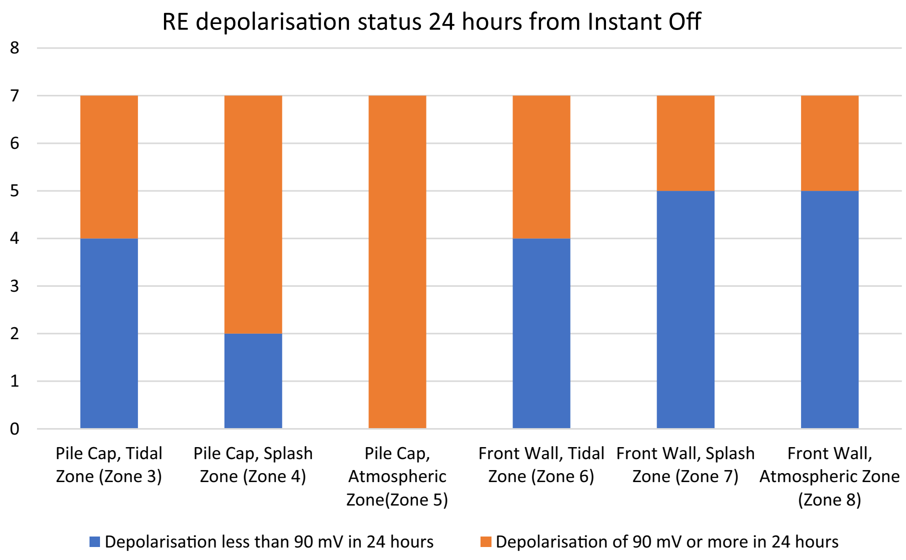


Fig. 12 Showing the depolarisation status of REs 24 h after Instant Off

these are located in the tidal zone of the front wall in Zone 6. Hence, these two locations are identified as not achieving the 24 h, 100 mV decay criteria and that protection is not achieved. Analysing the extended potential decay data (72 h), Ref. 4 and Ref. 16 both still display a negative decay, while all other RE still achieve the protection criteria.

After 72 h an additional 6 achieve a 100 mV decay, corresponding to the extended potential decay criterion. The depolarisation status of REs at the end of 72 h is shown in Fig. 13 below.

These include the four REs that achieved 90 mV depolarisation at 24 h (REs. 3, 7, 9 and 36), corresponding to three additional REs in the atmospheric zone in the front pile cap and one in the tidal zone of the front pile cap. The two additional RE to achieve the 100 mV decay after 72 h which had not achieved 90 mV depolarisation at 24 h are Ref. 13, also in the tidal zone of the front pile cap and RE 35 in the spray zone of the front wall. It was also noted that one RE that had achieved 100 mV at 24 h did not maintain the 100 mV decay at 72 h, Ref. 31, which is located in the tidal front pile cap.

4.2 Discussion—absolute potential and absolute passive criteria

A single RE achieves an instant off potential more negative than − 720 mV, Ref. 18[1] This is located in

[1] That the most negative RE is located in the Atmospheric zone is unexpected. It is anticipated by the authors that the RE are within the correct zones however local environments may be different which accounts for the variations in the potentials. This would account for other unexpected variations in the potential of RE 18 which clearly show a tidal cycle, something not expected for a RE in the Atmospheric Zone.

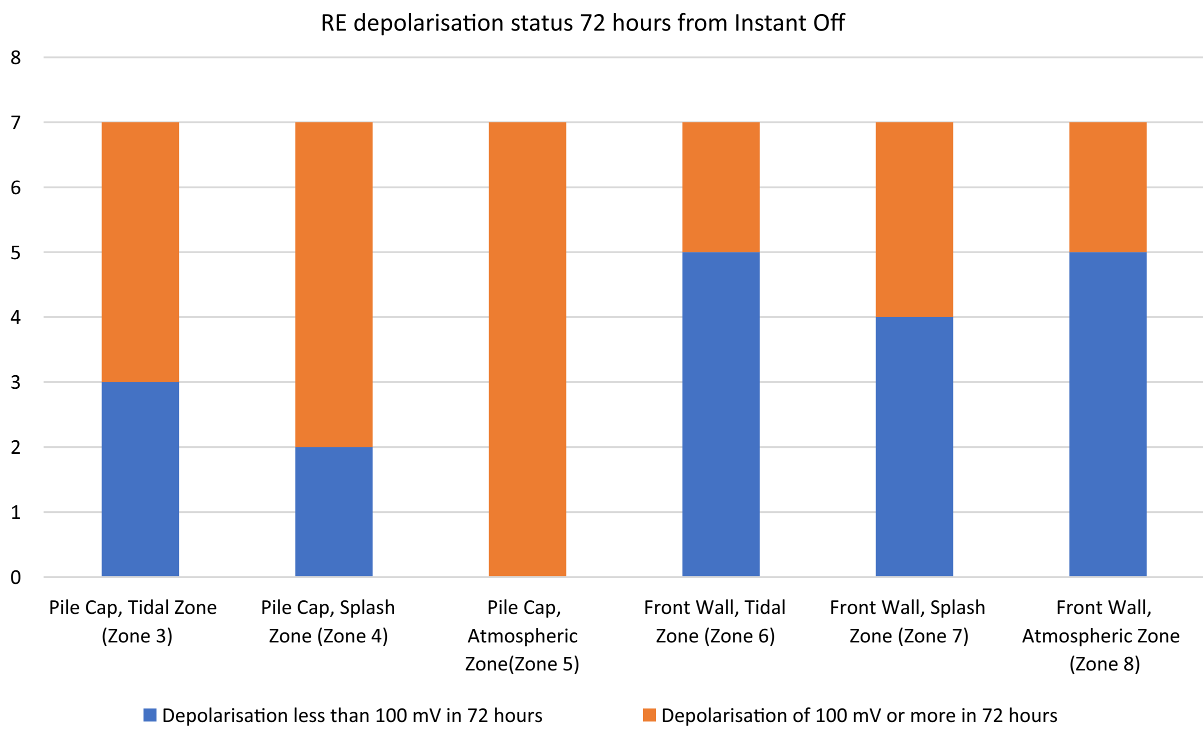


Fig. 13 Showing the depolarisation status of REs 72 h after Instant Off

the atmospheric zone of the front wall, Zone 8. This RE also satisfies the 100 mV decay criterion. With respect to the absolute passive criterion of achieving a consistent potential less negative than − 150 mV, a total of nine RE satisfy this criterion included four which achieve the absolute criterion of − 150 mV after 72, not 24 h. Of these four REs three are in the atmospheric zone for the front wall and the final one is in the splash zone of the front wall. That these REs required more time to achieve the criteria is attributed to their location in the atmospheric zone. It would be expected that the electrodes in the atmospheric zone will not be influenced by the tidal pattern, as observed in Figs. 5 and 8 and hence have more positive potentials. Thus, given their more positive instant off potentials, there is a reduced likelihood that they will be able to achieve the 100 mV decay criterion.

Based upon the four specified criteria in AS 2832.5 [21] the data demonstrates twenty-six of the forty one RE satisfy at least one of the criteria and a further one was close to satisfying the 24 h decay criterion. These correspond to sixteen out of twenty-one of the RE in the front pile caps, including all in the atmospheric zone and ten out of twenty-two in the front wall, with five out of seven in the atmospheric zone passing one criteria. In both the front wall and the pile caps only six RE in the tidal zone achieve any of the required criteria. Across the front wall and the pile cap splash zone eight RE achieved at least one of the criteria.

4.3 Discussion—impact of the water anode ICCP system

The deactivation of the water anodes was undertaken 2 h after the deactivation of the concrete ICCP system (approx. 5 h into monitoring of the ICC system) and was then re-energised after a 48 h period (approx. 53 h into monitoring of the ICCP system). Following deactivation of the system a 10–25 mV positive shift in potential was observed in the majority of RE, though a shift of up to 50 mV was observed for some RE in the tidal zone, Fig. 14. The shift in potential is most evident in the tidal and splash zones, with a smaller or in some case no shift observed in the atmospheric zone. This is attributed to the elements in the tidal and splash being in direct contact with the water. In general, larger shifts are observed for those RE displaying the most negative instant off potentials,

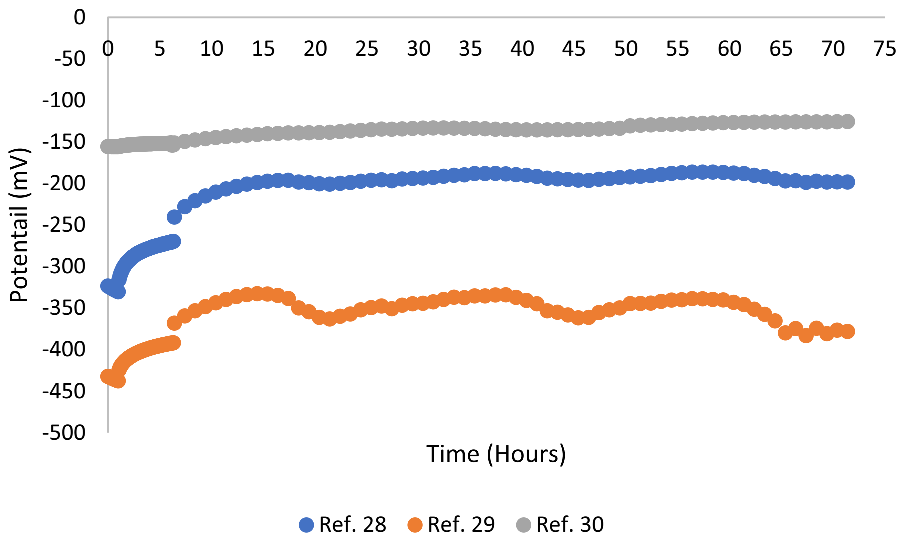


Fig. 14 Decay curves for reference electrode 28 (tidal, zone 6), reference electrode 29, (splash, zone 7) and reference electrode 30 (atmospheric, zone 8), Front Wall, Water Anode Re-Activation Period

which is attributed to the location of these electrodes. The exact location of the RE is not provided in the reports and it is thought that some electrodes may be in concrete elements that are submerged at high tide and so more exposed to the effects of the water ICCP system.

The positive shift noted is attributed to the loss of current to the reinforcing steel otherwise provided by the water anodes. The de-activation of the water anode system 2 h post de-activation of the Berth 6 ICCP means that this will contribute to the 24 h and 72-h decay values. Accounting for the positive potential shift observed at the point of de-activation of the water anodes in the 24-h decay values would mean four RE would no longer achieve the 24-h 100 mv criterion.

Re-activation of the water anodes had no observable impact on the steel potentials of any of the electrodes. The small depolarisation observed when the system is de-activated suggests that the water anodes are providing a minor contribution to the "residual" protection of the steel. However, it is difficult to quantify the magnitude of this contribution given that the depolarisation is not observed in all RE and no discernible impact is observed when the system is re-energised. It is most likely that any protection from the water anodes will be in the tidal zone as this is in direct contact with the water and may also be dependent on the point in the tidal cycle when the de-activation and re-activation occurred. Thus, it is likely that the water anodes are providing a small contribution towards the protection of the reinforcing steel in the tidal zone. However, are providing a minimal contribution in protecting the reinforcing steel in the concrete.

4.4 Discussion—reactivation of REs

Previous research has highlighted that the potential decay versus time can also be used to provide an indication of the passivity of the reinforcing steel following de-activation of an ICCP system [24]. Re-initiation of corrosion is characterised by a marked shift to more negative potential values, especially a shift to a potential more negative than the instant OFF value. This behaviour can be distinguished from short term negative excursions attributed to the tidal variations as being a sustained negative trend over time and being independent of the tidal cycle. All of forty-one RE displayed a more positive values at the conclusion of the trial than their instant off values. Twenty-eight of the REs have values more positive than 100 mV compared to the instant off potential with only six REs less than 50 mV more positive compared to the instant off potential. Of these six RE, three are in the atmospheric zone of the front wall all of which had potentials more positive than − 150 mV at the conclusion of the trial and are hence considered to be passive. The least positive is RE 4, corresponding to the tidal zone in the front wall which is only 4 mV more positive than the instant off at the conclusion of the test, though this is more positive than the 24 h OFF potential. Interestingly only one RE is more negative at the conclusion of the trial than the 24 h off potential, RE 31, Zone 3 in the tidal zone of the front pile cap, though this is still more positive than the instant OFF potential by 47 mV, while RE 33, atmospheric, front pile cap, Zone 5, has the same potential at the conclusion of the trial as the 24 h depolarised potential but in this case is 157 mV more positive than the instant OFF reading.

Indeed, at some point in the 84 days, all electrodes have more positive potentials following de-activation when compared to their instant off value. If this positive decay is adopted as an indication of passivity, the data implies that residual protection is being achieved in all locations for a period of time post de-activation.

Only one RE displayed evidence of a sharp fall in potential to more negative values, Fig. 15, which has previously been suggested as indicative of re-initiation of corrosion [17]. RE 19 (71 days) is located in the tidal zone of the front wall cap in Zone 3. However, an additional fifteen RE display a shallow reduction in potential trend during the last 20 days of the trial. It is not surprising that the re-initiation of corrosion is first observed in the tidal zone as this corresponds with the most aggressive environment, both with respect to chloride ingress and to the wet/dry cycles both of which promote corrosion. Thus, twenty-five RE maintain a positive trend over the entire 84 days.

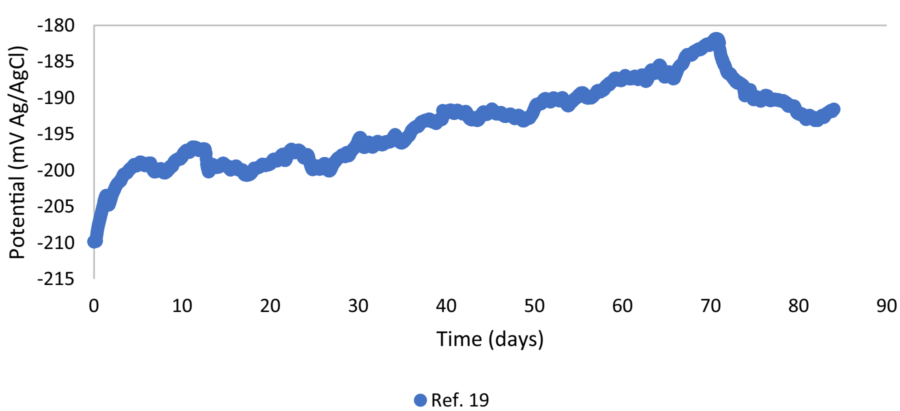
In total twenty-three RE (56%) satisfy the 100 mv decay criterion (24 and 72 h) as stipulated in the Australia Standard [20], nine RE (22%) the absolute criterion of − 150 mv and one (2%) the − 720 mV criterion. Combining the criteria identified twenty-one RE (51%) satisfy at least one of the criteria. An earlier study at the same Port [17] on a 35 year old Berth with ICCP applied incrementally over the 10 years prior to the trial showed 95% of the elements achieving one of the protection criteria when the ICCP was de-energised. Following de-energisation 79% displayed passivity based upon a positive decay, though only 34% maintained a potential more positive than − 150 mV over the 122 day period of the trial. In another study on residual protection 96% of 72 beams in a trial on a 45 years old marine structure on which ICCP had been applied for eight years satisfied the Australian Standard, with regard to protection criteria [19]. At the end of this 106 day trial 7% of the beams maintained a steel potential more positive than − 150 mV, and 35% maintained protection based on a positive decay trend. This compared to 22% of elements in this trial maintaining a potential more positive than − 150 mV and 61% of elements when applying the positive trend criteria.

5 Conclusions

Following the monitoring of the de-activation of a 20 years old ICCP system installed on a 55 years old wharf all forty-one RE across in various elements of the berth show a positive shift in potential over the 84 day trial period which suggest some level of Residual Protection due to the persistence of passive conditions was afforded during this time. The following major conclusions are drawn;

- Following de-activation seventeen RE satisfy the 24 h decay criterion of at least 100 mV decay from the instantaneous OFF potential within 24 h and twenty-two satisfy the 100 mV decay after 72 h.

Fig. 15 Decay curves for reference electrode 19 (tidal, zone 3), sharp decrease, 71 days



An additional five RE had a decay of greater than 90 mV. One RE achieves a more negative instant off potential than − 720 mV and nine RE achieve the absolute criterion of -150 mV. In total twenty-six of the forty-one RE satisfy at least one of the criteria and a further one is close to satisfying the 24 h decay criterion.

- Following de-activation of the water anode system a small positive shift in potential was observed in most RE, while no clear shift in potential was observed when the water anodes were re-activated.
- The effect of the tidal action, in particular neap tides, could be clearly observed in the RE in the tidal and splash zones. This led to a short-term negative shift in potential. This was not believed to be indicative of re-activation of corrosion, with a positive trend being clearly evident in the potential decay despite these negative incursions.
- During the trial only one RE displayed a sharp decrease in potential, which suggests re-initiation of corrosion, in the tidal zone. A further fifteen additional RE displayed a shallow decrease in their potential in the final 20 days of the trial, which may also indicate a reduction in protection.
- In total 25 out of the 41 (61%) maintained a positive trend at the conclusion of the trial.

The results indicate that observable residual protection is afforded to the structure, particularly in the atmospheric zone. The presence of residual protection in structures could provide additional options to asset managers for the management of structures where the structure is close to the end of the service life. Thus, a structure may continue to function with no additional maintenance/rehabilitation due to the residual protection from the ICCP, or may require reduced protective measures in the knowledge that corrosion will not re-initiate in the atmospheric elements of the structure. In addition, it may also be possible to de-activate the ICCP in certain elements in the knowledge that they will be protected until the end of service life. These options could then provide cost savings to the asset manager and owner. Further research and monitoring is required to fully understand the level and duration of protection afforded. Knowledge of the total current applied to each zone over the operational lifetime of the structure would enable a correlation to be made between the depolarisation achieved and the potential for residual protection to occur. However, the data does support the previous anecdotal observations that ICCP systems do provide residual protection once de-activated.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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