Cathodic Protection of concrete structures: a case study of Madeira airport.

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Abstract. Reinforced concrete structures located near the coast are particularly prone to corrosion due to the presence of chloride ions in the air surrounding the structures. This article presents a practical case study of the implementation of cathodic protection (CP) to a 4,000 m² area reinforced concrete structure near Madeira International Airport, Portugal. This paper describes the corrosion condition of the columns and arcades, based on a 2018 inspection report by the regional civil engineering laboratory (LREC) and highlights the key aspects of the design, the installation and the construction works as well as the first-year monitoring results of the cathodic protection system. These results demonstrate that the application of cathodic protection (CP) is an effective solution for mitigating corrosion and extending the service life of this structure.

1 Introduction

This structure was built to support the regional highway at Madeira International airport, and it is critical for the airport's operational safety. This concrete structure with 10 arcades and 11 columns was designed by Edgar Cardoso and Hidroservice, Engenharia de Projetos, and it was originally built in 1979 (Figure 1).

Figure 1 – Front view of the infrastructure.

The 2018 inspection report [1] confirmed that chloride contamination at reinforcement level had already occurred, significantly surpassing the commonly accepted threshold limit for corrosion initiation (0.4% per cement mass) due to the continuous exposure to a harsh maritime environment.

As illustrated in Figure 2 in Arcade 10, the chloride content varied from 1.2 % per mass of cement at the surface to values as high as 0.66 % per mass of cement, at 100-130 mm concrete depth. However, at the reinforcement level (30-50 mm) the chloride content measured 0.74 % per cement mass.

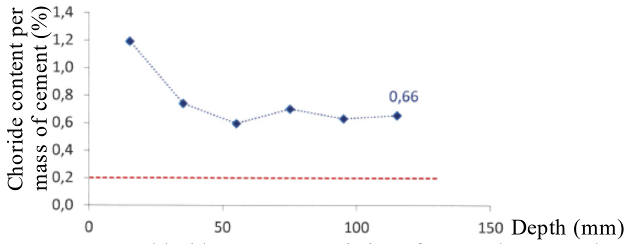

Figure 2 – Chloride content variation for arcade 10 and column 11 [1].

The chloride content at the reinforcement level (30-50mm), varied between a minimum of 0.56% (arcade 8) and a maximum of 2.5% (arcade 10). Thus, these values far exceeded the corrosion initiation threshold which indicated that corrosion is actively propagating throughout the structure, leading to substantial and visible damage, particularly to the columns. (Figure 3).

Figure 3 – Pre-existing damage in the columns [1].

The inspection highlighted extensive delamination exceeding 50% in the columns while the arcades showed a delamination area below 10% (Figure 4 and Figure 5).

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Figure 4 – Condition of Arcade 7 before intervention [1].

Figure 5 – Condition of Arcade 3 before intervention [1].

Despite providing excellent structural properties, the presence of the existing high-strength concrete (C50/60) complicated the application of conventional rehabilitation techniques. The initial strategy recommended consisted on the removal of the outer 10cm thick concrete layer in all arcade surfaces, the replacement of the corroded reinforcing steel with new steel reinforcement, if necessary, and the application of an overlay with repair mortars. This would require a staggered and extended intervention with heavy and costly steel support towers and eventually with limitations in the highway traffic above. In this context, cathodic protection (CP) was identified as a cost-effective solution to the problems of this structure.

2 CP design

The anode used was an activated titanium mesh ribbon covered with mixed-metal oxides (Ti/MMO). The ribbon used is 20 mm wide and 1mm thick, with a current capacity of 5.3 mA/m and a current density of 110 mA/m2. The ribbons were connected with the current distributor through spot welding. The current distributor was a solid titanium ribbon, which measured 15 mm wide and 0.9mm thick. The ribbons were installed with a spacing of 25 cm. The anodic system in each arcade was divided into two electrically independent zones, with a total of 20 zones for the structure. Three anodic and cathodic connections as well three monitoring connections, were established per zone. Each monitoring connection consisted of one testing connection, one manganese dioxide electrode (MnO_2) and a Ti/MMO potential decay probe. A total of 120 sensors were installed in the structure.

3 CP installation

In accordance with the project specifications, each arcade was marked with double lines for ribbon placement at 25 cm intervals. These lines were cut with an angle grinder and the slots were easily opened with a demolition hammer.

After opening the slots, all exposed steel bars or wires were covered with the mortar that was subsequently used to fill the slots (Figure 6). This was done to avoid any contact between the anode (Ti/MMO ribbons) and the cathode that could cause short circuits.

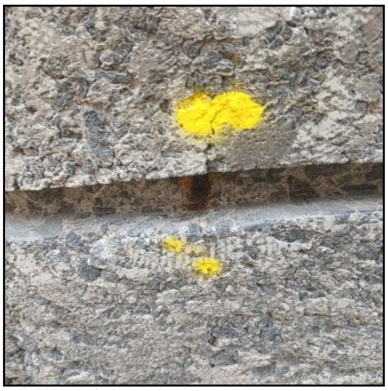

Figure 6 – An exposed steel bar in the slot.

According to the design layout, three openings were done in the concrete surface to install the anodic and cathodic connections, as well as the addition of three openings to install monitoring sensors in each zone.

Electric continuity tests were performed between reinforcing steel bars at various locations and between the internal and the external reinforcing layers for each zone. No discontinuities in the reinforcement bars were found and good electrical continuity was also found between the internal and the external reinforcing layers.

The Ti/MMO ribbons were installed along the horizontal slots, while the solid titanium ribbons (current distributor) were installed along the three vertical slots, in accordance with the project specifications. The ribbons were divided into two equal areas: the lower and upper zones (zones 1 and 2, respectively).

The mesh ribbon installation was made in the following steps: first, the slot was filled with a mortar layer; then, the titanium ribbon was installed (Figure 7); and, finally, another mortar layer was applied.

Figure 7 – Anode installation.

Through spot welding, the Ti/MMO mesh ribbons and current distributor ribbons were connected (Figure 8).

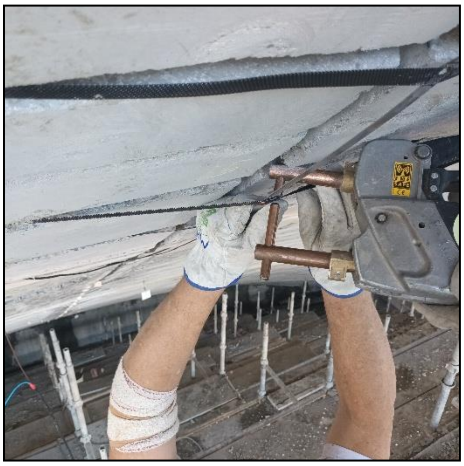

Figure 8 – Spot welding for anode ribbons.

Current injection tests were conducted immediately after finishing the installation of the anode ribbons in each zone, in order to guarantee that the cathodic protection system was properly installed.

The anodic and cathodic connections and monitoring connections were installed, and the corresponding cables were installed in separate slots leading towards the columns at the bottom of the arcade for connection to the power supply unit.

Finally, the power supply and monitoring unit were installed in a housing built for that purpose (Figure 9 and Figure 10). This unit provides the direct current required for protection and allows the remote control and monitoring of the system.

Figure 9 – Power supply unit.

Figure 10 – Power supply unit.

4 Monitoring results of CP during a year-long period

The system was commissioned in October 2023. In order to assess the effectiveness of the cathodic protection system, 24-hour depolarisation tests were carried out in January, March, July and October. In November, the structure was allowed to depolarise for a 48-hours period. These tests were performed remotely through the UA unit. The system was programmed to carry out a 24-hours or 48-hours depolarisation test and record the following:

- the output current and voltage from the power supplies before starting the test;
- the ON potential and Instant OFF potential;
- the OFF potential at 1-hour intervals.

The test consisted of recording the ON and Instant OFF potentials, followed by switching off the current in all zones for 24/48 hours and monitoring the decay of the OFF potential (i.e. the variation of the OFF potential over time with the current switched off). The purpose of the test was to determine the depolarisation value (potential decay) obtained over 24 and 48 hours and to verify compliance with the protection criteria in each zone.

The depolarisation value obtained at 24 hours is calculated as the difference between the OFF potential measured 24 hours after the current is switched off and the Instant OFF potential. A similar calculation is performed for the depolarisation obtained at 48 hours.

At the end of each depolarisation test, and after analysing the results, the current was either increased or decreased in the zones where it was deemed necessary. If the protection criteria were not met, the current was increased. In some zones, the current was reduced because the 24-hour depolarisation results exceeded 100 mV. A summary of the current adjustments made to each zone is briefly presented in Table 1.

Table 1 – Current values summary during first year.

[illegible]	[illegible]	Current (A)

		Oct. 22, 2023	Nov. 7, 2023	Feb 16, 2024	Mar. 3, 2024	Apr. 19, 2024	May 22, 2024	Sep. 17, 2024	Nov. 1, 2024
A1	Z1	1	0.5	0.5	0.5	0.5	0.5	0.5	0.5
	Z2	1	0.5	0.4	0.4	0.4	0.4	0.4	0.4
A2	Z1	2	1	0.8	0.8	0.8	1	1	1
	Z2	2	1	0.9	0.9	0.8	1	1	1
A3	Z1	2	1	0.8	0.8	0.8	0.8	0.8	0.8
	Z2	2	1	1	1	1	1	1	1
A4	Z1	2	1	1	1	1	1	1	1
	Z2	2	1	1.25	1.5	1.5	1.5	1.5	1.5
A5	Z1	2	1	1	1.25	1.25	1.25	1.25	1.25
	Z2	2	1	1	1	1	1	1	1
A6	Z1	2	1	0.8	0.8	0.8	0.8	0.8	0.8
	Z2	2	1	1	1	1	1	1	1
A7	Z1	2	1	1.25	2	3	3	3	3
	Z2	2	1	1.25	2	2	2	1.5	1.5
A8	Z1	2	1	1	1	1	1	1	1
	Z2	2	1	1	1	1	1	1	1
A9	Z1	2	1	1	1	1	1	1	1
	Z2	2	1	0.8	0.8	0.8	0.8	0.8	0.8
A10	Z1	1	0.4	0.4	0.3	0.3	0.3	0.3	0.3
	Z2	1	0.5	0.5	0.35	0.35	0.34	0.35	0.35

The results of the depolarisation tests carried out in October are presented as an example for Arcade 1 (Zones 1 and 2 - Figure 11 and Figure 12).

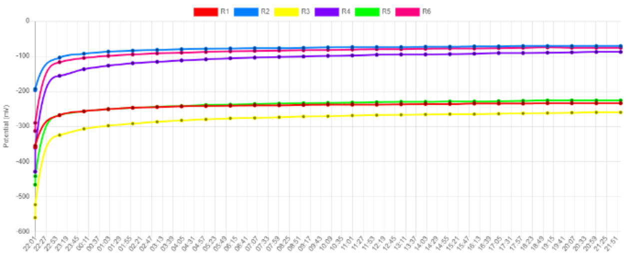

Figure 11 – Depolarization graph for Arcade 1, Zone 1 (October,2024).

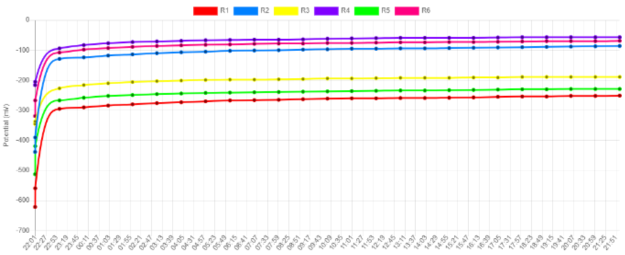

Figure 12 - Depolarization graph for Arcade 1, Zone 2 (October,2024).

Data from the depolarisation tests carried out in November is presented in Table 2 for Arcade 1. An analysis of the results shows that:

- The criterion of achieving a **100 mV** potential decay in 24 hours was met in all zones.
- In November 2024, the potential recorded in all reference electrodes, 48 hours after switching off the current (48h Off potential), was less negative than -150 mV Ag/AgCl/0.5 mol/l KCl (-314 mV Mn/MnO2). This indicates that one year after the system was energised, the reinforcement steel at all monitoring points is in a passive state, in accordance with ISO EN 12696.

Table 2 – Potential decay in 24h and 48h for Arcade 1.

Zone	Sensor	Pot. ON	Pot. IO	24h Pot. Off	48h Pot. Off	24h DESP	48h DESP
		(mV)					
Zone 1	ER1	-362	-359	-235	-232	124	127
	S1	-203	-198	-74	-71	124	127
	ER2	-580	-539	-262	-253	277	286
	S2	-459	-379	-90	-82	289	297
	ER3	-483	-457	-227	-223	230	234
	S3	-331	-305	-77	-74	228	231
	Average					**212**	**217**
Zone 2	ER1	-645	-578	-254	-245	324	333
	S1	-463	-410	-90	-83	320	327
	ER2	-354	-345	-191	-187	154	158
	S2	-227	-214	-59	-56	155	158
	ER3	-543	-438	-234	-228	204	210
	S3	-346	-285	-73	-68	212	217
	Average					**228**	**234**

After the November 2024 depolarisation, and given that the values indicate the reinforcement steel is in a passive state, the current was reduced in all zones. The aim was to achieve depolarisation values much closer to 100 mV, on average.

5 Conclusions

The application of cathodic protection to the reinforced concrete structure at Madeira Airport proved to be effective in mitigating corrosion primarily caused by high chloride concentrations, thus extending the service life of the infrastructure. After one year in operation, all depolarisation tests met the 100 mV criterion within 24 hours, confirming the system's suitability even under highly aggressive maritime conditions.

Continuous monitoring, via a dedicated power supply unit, enables remote management of the system's performance. This monitoring confirms that the reinforcement remains in a passive state, in accordance with ISO EN 12696. The ability to periodically adjust the current in each zone, based on depolarisation test results, ensures both energy efficiency and ongoing compliance with protection criteria.

Moreover, this method has proven to be economically advantageous compared to more invasive interventions requiring extensive concrete removal and potentially lead to traffic disruptions. Thus, cathodic protection stands out as a rapid and low-impact solution for corrosion control in concrete structures exposed to aggressive environments.

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References

1. 28-DEM-2018, Avaliação da Integridade da Estrutura de Contenção da Cabeceira 06 do Aeroporto da Madeira, Technical report, LREC, 2018
2. ISO EN 12696, Cathodic protection of steel in concrete