XVI International Conference on Durability of Building Materials and Components
DBMC 2023, China
K.F. Li and D.P. Fang (Eds)

Assessment of the Impressed Current Cathodic Protection System after 4 Years Operation: Evolution Over Temperature and Time of the Applied Current and Tension on Anodic Zones of the Saint-Cloud Viaduct (France).

J. Ducasse-Lapeyrusse[1, 2], V. Bouteiller[3], O. Lesieutre[4], E. Marie-Victoire[1, 2], M. Bouichou[1, 2], G. Damien[5], V. Martinet[5],and C. Annede-Villeau[6]

[1] Centre de Recherche sur la Conservation (CRC), Muséum national d'Histoire naturelle, CNRS, Ministère de la Culture. France,

[2.] Laboratoire de Recherche des Monuments Historiques (LRMH), Ministère de la Culture, 29 rue de Paris, 77420 Champs-sur-Marne, France, jean.ducasse-lapeyrusse@culture.gouv.fr, elisabeth.marie-victoire@culture.gouv.fr, myriam.bouichou@culture.gouv.fr

[3]Université Gustave Eiffel, MAST-EMGCU, F-77454 Marne-la-Vallée, France, veronique.bouteiller@univ-eiffel.fr

[4]Résilience & Maintenance du Béton, 3 chemin du Charrat 69250 Fleurieu-sur-Saône, France, olivier.lesieutre@resmaibe.fr

[5]Direction Régionale et Interdépartementale de l'Environnement, de l'Aménagement et des Transports d'Île-de-France (DRIEAT), DiRIF/SGPR/DOA, France; guillaume.damien@developpement-durable.gouv.fr, victor.martinet@developpement-durable.gouv.fr

[6]Freyssinet International & Cie, Technical Department, 92506 Rueil Malmaison Cedex, France, camille.annede-villeau@freyssinet.com

Abstract. *This paper presents the feedback of the Impressed Current Cathodic Protection (ICCP) system implemented on a road bridge, the Viaduct of Saint-Cloud, constructed in the 1970s in France. After a test trial in 2012, the full-scale ICCP system was energized in 2018. It consisted of 44359 discrete titanium anodes implemented on the lateral segment webs on both sides of the Viaduct, distributed in 212 anodic zones on one side and 153 anodic zones on the other side. The four years monitoring data include the variations of the applied current and tension on anodic zones, their polarization, etc. This paper focus on the global resistance of the circuit for the different anodic zones. The circuit resistance shows first the influence of the temperature. The differences between anodic zones and their evolution over time also bring more information about the environment of the anodes and the reinforcements. The analysis of the response of the circuit reveals the heterogeneity of an actual and large-scale ICCP system and provides important feedback to an appropriate ICCP design for durable cathodic protection.*

Keywords: *Impressed Current Cathodic Protection; Durability; Reinforced concrete structures; Case study; Assessment.*

1 Introduction

The Saint-Cloud Viaduct is a large highway bridge, allowing more than 120,000 vehicles per day to cross the Seine River between the cities of Boulogne and Saint-Cloud in the West of Paris (Figure 1). Built between 1972 and 1974, the viaduct is a prestressed segmental concrete bridge with a total length of 1103 meters. The deck is a three-cell box girder constituted by 498 precast concrete segments with a constant height of 3.60 m, a width of 20.40 m and an average length of 2.25 m. The lateral webs have a thickness of 25 cm (Mathivat, 1973). The "*Direction* *des routes d'Île-de-France*" (DiRIF), a public service for highways in the Paris region, is the current owner and manager of the structure.

Figure 1. Picture of the Saint-Cloud Viaduct (Saint-Cloud city in the background).

Disorders were observed in 2012 on the lateral webs of the segments (rust stains, concrete cracks and spalling damages). Due to a faulty drainage system, chlorides coming from the de-icing salts flew along the segments leading to chloride-induced corrosion of the steel reinforcement. The bridge assessment was first based on visual inspections and delamination survey (rust stains, concrete cracks and spalling damages). In addition, profile chloride contents were analyzed on cores drilled on a selection of segments which results confirmed the chloride-induced corrosion. The chloride concentrations were found to be highly variable, even within the same segment. In areas where water flowed, as indicated by staining, the concentration of chlorides at the depth of reinforcement was greater than the threshold concentration for the initiation of corrosion (0.07% by weight of concrete or 0.4% by weight of cement). Various corrosion diagnostic techniques were used, including resistivity, potential mapping, and linear polarization resistance measurements. The results indicated that corrosion of the reinforcements was active and spreading from the top of the segment webs, following the flow of water containing chlorides. Due to limitations related to the traffic disruption, reduction of noise and dust in a dense populated area, the concrete removal was challenging and not compatible with the structural load capacity of the bridge. Impressed Current Cathodic Protection (ICCP) system seemed to be the most relevant solution in this context. Only physically deteriorated concrete need to be removed while chloride-contaminated but sound concrete can be left in place. The selection of an ICCP system over a galvanic one was based on the need to adjust current densities due to the varying levels of chloride concentrations and the possible requirement of a high driving voltage due to the resistivity of the concrete (Bennett & Turk, 1994; Broomfield, 2006; Pedeferri, 1996, 2018; Wilson et al., 2013). Discrete titanium anodes were preferred over a titanium mesh due to weight limitations, as an additional layer of concrete was not feasible. From 2011 to 2012, a field trial was performed on one segment on pier (P2) and two adjacent span segments (Bouteiller et al., 2015, 2019). Highly recommended (Sohanghpurwala, 2009), the field trial provided technical data helpful for the design and the commissioning of the full-scale application of ICCP to the Saint-Cloud Viaduct.

2 Presentation of the ICCP System

The principle of the ICCP system used is presented in the following figure (Figure 2). The ICCP was designed as two independent systems: one protecting the side of the Viaduct close to the Boulogne direction traffic lane and one protecting the opposite side, close to the Saint-Cloud direction traffic lane.

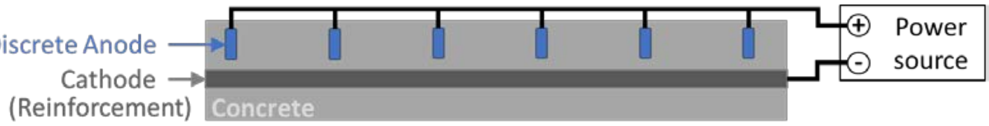

Figure 2. Scheme of Impressed Current Cathodic Protection (ICCP) system using discrete anodes.

The lateral webs of each segment were divided from top to bottom into 4 sub-zones:
- "Top Outside" with 10 anodes implanted from the outside,
- "Top Inside" with 10 anodes implanted from the inside,
- "Central" with 25 anodes implanted from the inside and
- "Bottom" zones with 10 anodes implanted from the inside.

The discrete anodes utilized in this system were made of Mixed Metal Oxide (MMO) coated titanium. These anodes had an active length of 17 cm and a diameter of 8 mm. In addition they had a 38 mm long head containing a 220 Ω resistor in order to optimize current distribution within a given zone and prevent local current leakage. There was a 40 cm exclusion zone on the top due to the proximity of internal prestressed tendons. The anodic zones were constituted by gathering the sub-zones of 6 to 10 lateral segment webs (Figure 3). There is at least one reference electrode for each anodic zone.

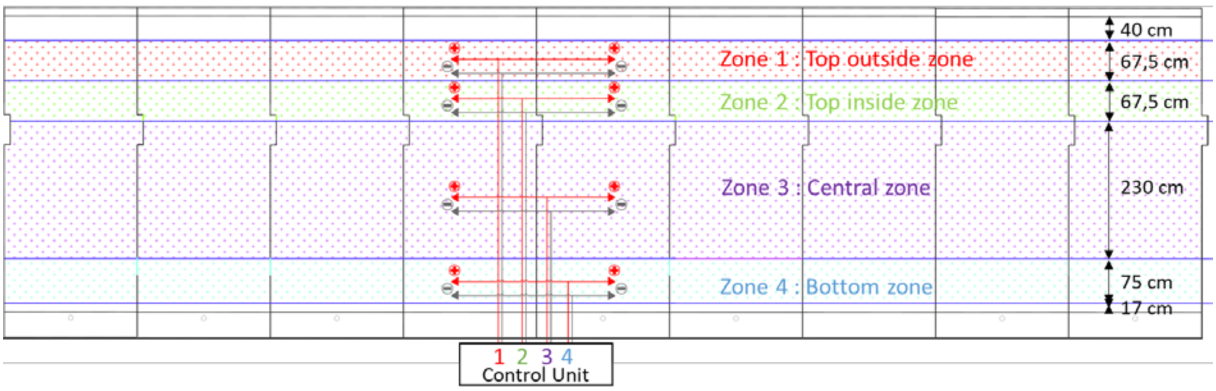

Figure 3. Four anodic zones grouping 9 segments controlled by one secondary device.

One Central Control Unit (CCU) collected the data coming from 53 secondary devices (Control Unit) controlling 212 anodic zones on the Boulogne side and another CCU collected the data coming from 40 secondary devices controlling 153 anodic zones on the Saint-Cloud side. The ICCP system on the Boulogne side was energized on January 17, 2017, and the one on the Saint-Cloud side on February 17, 2018. To assess the performance of the ICCP system, the measurement of the potential decay, "criteria b", according to the Standard ISO 12696 (AFNOR, 2022) was used. More information about the ICCP system of the Saint-Cloud Viaduct, the measurement of the potential decay, discussion about the current densities (mA/m² of steel) can be found in a previous publication (Ducasse-Lapeyrusse et al., 2023). This paper focus only on the circuit resistance of the anodic zones constituted by 10 lateral segment webs, on the Saint-Cloud side, i.e., 64 anodic zones (16 “Top Outside”, 16 “Top Inside”, 16 “Central” and 16 “Bottom” zones) controlled by 16 Control Unit.

3 Results: Circuit Resistance, Temperature and Evolution with Time

The control units, in order to provide the current necessary for the cathodic protection, must adjust the voltage. For each anodic zone, the resistance of the circuit can be calculated by dividing the voltage by the applied current measured at the rectifier. The remote monitoring system collects voltage and the current of each anodic zone every 6 hours, the data presented in this analysis spanning from March 2018 to October 2021. There is some missing data during the first few months after the energizing of the ICCP system due to some adjustments. The evolution during four years of the mean daily resistance value for each type of zone (16 anodic zones for each type) are presented in the following figure (Figure 4). The figure also presents the average maximum and minimum temperature values from the preceding five days.

The “Top Outside”, “Top Inside” and “Bottom” zones have 10 discrete anodes implanted on each segment web (subzones). The “Central” zones have 25 discrete anodes implanted on each subzone. The subzone circuit, with 10 or 25 anodes, could be assimilated to 10 or 25 resistors in parallel. Then, to compare the different zones, a factor of 25/10 is applied to the central zone (dashed line “Central modified” in Figure 4).

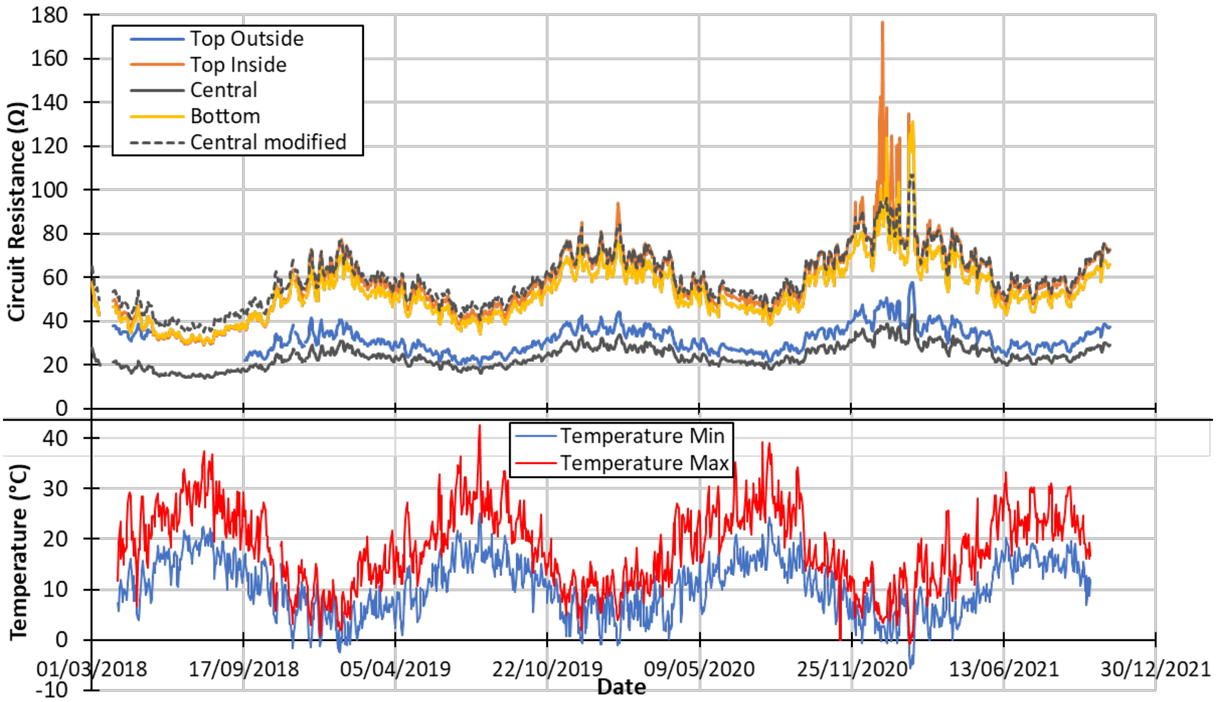

Figure 4. Mean circuit resistance of the different zones constituted by 10 segment webs and maximum and minimum temperature according to the date.

The circuit resistance is clearly correlated to the temperature; the resistance decreases as the temperature is rising. There are some outliers due to freezing temperature where the resistance can reach very high values. The resistance of the anodic circuits can vary in the ratio of one to two and are in good agreement with the findings of a previous publication (Ducasse-Lapeyrusse et al., 2023).

The "Top Inside", "Central" and "Bottom" zones show the same behavior and a similar circuit resistance (with the correction for the central zones). The "Top Outside" zones have a significantly lower resistance compared to the other zones. Since June 2018, the difference between the circuit resistance of the "Top Outside" zones and the average circuit resistance other zones remains constant, between 47% and 49%.

The following graphs (Figure 5) present the circuit resistance as a function of temperature. The circuit resistance data for each year is separated into two semesters, with the first semester covering January to June, and the second semester covering July to December. The full-temperature range is examined for each semester. To visualize the progression over time, the circuit resistances are depicted using a consistent color scheme, ranging from lighter tones representing the first semester of 2018 to darker tones for the second semester of 2021.

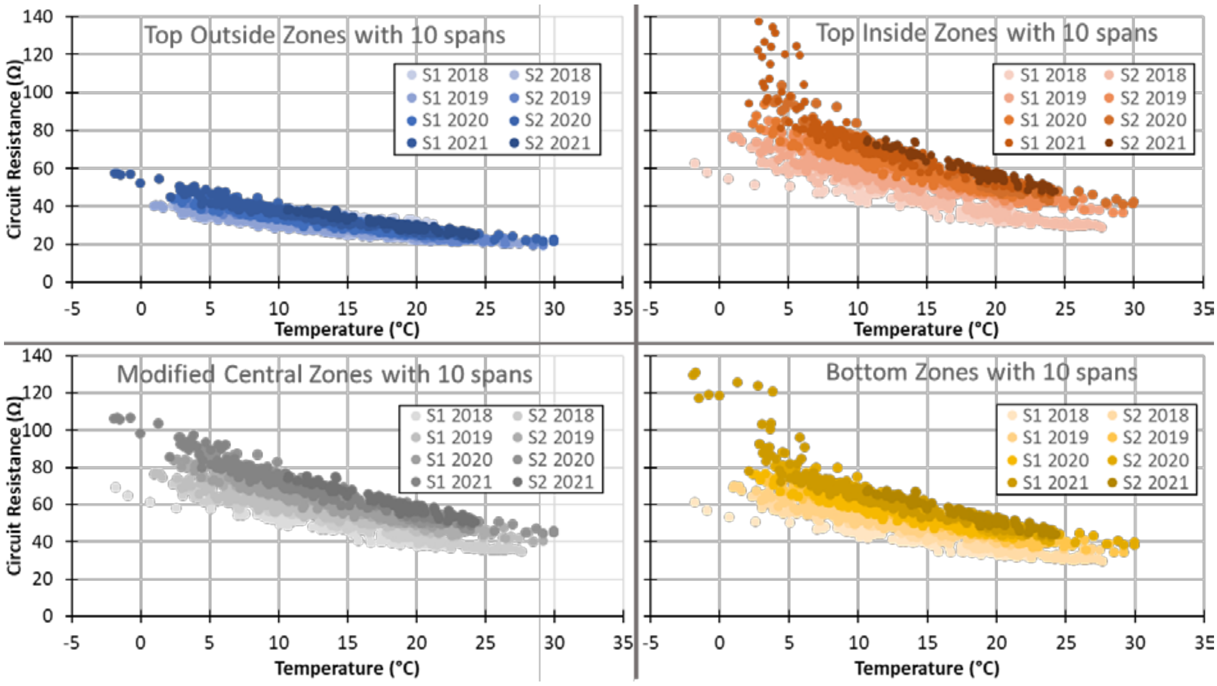

Figure 5. Mean circuit resistance of the 4 types of anodic zones as a function of temperature, for each semester between 2018 and 2021.

The circuit resistances of the "Top Inside", "Central" (modified with a factor of 25/10) and "Bottom" zones followed a similar pattern, and increase over time. On the contrary, the circuit resistances for the "Top Outside" zones have a limited evolution over time.

The following figure (Figure 6) present only the first semester of 2018 (on left) and the last semester of 2021 (on right).

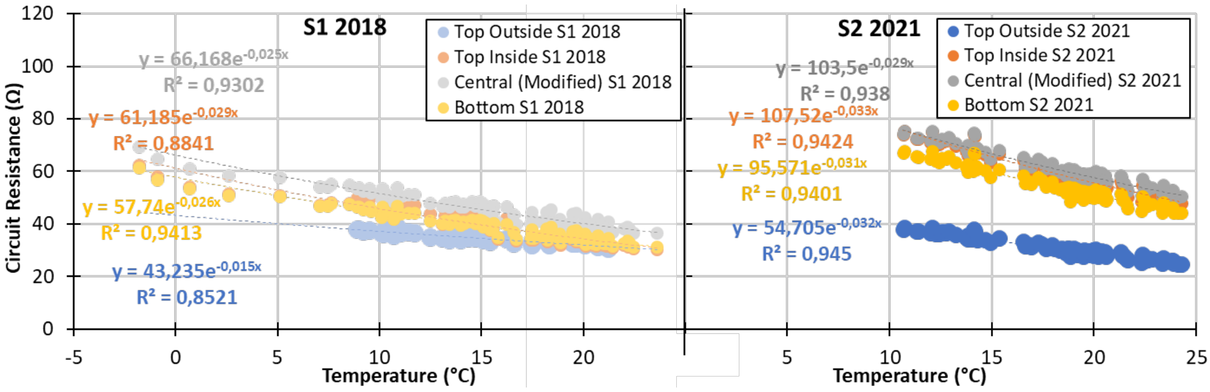

Figure 6. Mean circuit resistance of the 4 types of anodic zones as a function of temperature, for the first semester of 2018 and for the last semester of 2021.

For every semester, the mean circuit resistances of all the four types followed the Arrhenius law according to the following equation (1):

$$R = A.e^{BT} \tag{1}$$

where R is the circuit resistance, T the temperature, A and B are constants.
In the first semester of 2018, all types of zones exhibited similar circuit resistances. However, in the second semester of 2021, i.e more than 3 years after, a clear gap appeared between the circuit resistances of the "Top Outside" zones and the others, which had markedly increased.

4 Discussions

The comparison of several anodic zones, as well as the use of a factor of 25/10 as an adjustment factor for the central zones are based on simplifying assumptions. There are some heterogeneity even at a localized level. For exemple, the quality control procedures on site confirmed differences in circuit resistance from one segment to another in the same anodic zone. This paper focuses on a broader approach and looks of general tendencies that could emerge from large data treatment. Analysis of localized factors was carried out during the project, which will be the subject of other publications.

The temperature has a direct influence on the electrical resistance of the circuits which follow the Arrhenius law. But beyond the temperature effect, two main results come from the data treatments of the circuit resistances of the anodic zones:

- the circuit resistances of the "Top Inside", "Central" and "Bottom" zones were increasing over time;
- the "Top Outside" zones followed a different pattern from the other types of zones as the circuit resistances remained lower and relatively constant over time.

Some parameters influencing the resistance of the electrical circuit :

- The design of the anode implementation aimed to have a similar ratio of anode per surface of steel reinforcement in all zones, even if the "Top Inside" zone has a little less anodes per square meter of steel. The distance between anodes and reinforcements was also controlled in order to be homogeneous between all the zones. Implementing the anodes from the outside for the "Top Outside" zones should not have an impact, as the 17 cm active length (plus the 38 mm head) covers a substantial portion of the lateral web thickness (25 cm), similar to the implementation from the inside. Moreover, at the beginning, the circuit resistances of the four types of zones were similar, during the first semester of 2018. It should be noted that the contribution of the linear resistance of the cables to the overall apparent circuit resistance was negligible.

- The concrete water content is an important factor affecting the concrete resistivity. Exposure to rain and solar radiation have an effect on resistivity (Polder & Peelen, 2019). But in the present case, with a functioning draining system, repaired since the notification of its deterioration, and the global overview of data collected from an entire semester, the influence of precipitation and the water content should be similar between the four types of zones.

Then, the main factors that could explain the difference in resistance between the "Top Outside" zones and the other ones are related to the concrete resistivity and the interface condition between the reinforcements and the concrete. The evolution of the circuit resistance over time could be the consequence of the beneficial secondary effects of the cathodic protection, after corrosion protection. The cathodic processes occurring at the reinforcement surface result in a reduction of oxygen content and produce alkalinity on the reinforcement surface. Additionally, current circulation leads to a flux of chlorides from the cathode (the reinforcements) to the anode which reduces the chloride content on the surface reinforcements (Pedeferri, 1996). The migration of ionic species within the concrete, the compositional changes produced by the cathodic reactions at the reinforcements/concrete interface could explain the increasing resistance of the electrical circuit system.

The chlorides were brought by the water running from the top side of the segment webs. The "Top Outside" zones are the most contaminated by chlorides and have the most active corrosion. Compared to the "Top Inside", "Central", and "Bottom" zones, the "Top Outside" zones are expected to exhibit differences in the ion contents of the surrounding concrete, particularly in terms of chloride ions. This non homogeneous chloride content may lead to different levels of reinforcement corrosion and corrosion products, which can affect the electrical resistance between the steel and concrete. This hypothesis is supported by the assessment of these zones, as the "Top Outside" zones require a higher current density than other types of zones to meet "criteria b" according to the ISO 12696 standard (AFNOR, 2022), as previously presented in a publication (Ducasse-Lapeyrusse et al., 2023).

In a general point of view, electrical resistance considerations must be taken into account for an effective Cathodic Protection of the whole structure. The anodic zones should regroup areas with homogeneous conditions. A heterogenous current distribution inside an anodic zone could lead to overprotection or, on the contrary, to insufficient protection of isolated parts of the anode system (Hunkeler, 1992; Polder & Peelen, 2019). The vertical division "top outside", "top inside", "central" and "bottom", should have reduced heterogeneity. The appropriate definition of the anodic zones occurs at the very beginning of the ICCP design, based on the diagnosis and by analyzing the whole structure behavior.

5 Conclusion

In this paper, from the results of a 4 years ICCP system monitoring on the Viaduc de Saint-Cloud in France, a specific analysis of the resistances of the different anode circuits depending on the design has been conducted.

The following results were found:

- the circuit resistances of the “Top Inside”, “Central” and “Bottom” zones increased over the almost 4-year period;
- the circuit resistance of the “Top Outside” zone remained relatively constant over time and lower than for the other zones.

A resistance increase is likely correlated to the beneficial effects of the cathodic current such as ion migration in the concrete cover (such as chlorides) and compositional changes produced by the cathodic reactions leading to modification of the reinforcements/concrete interface. These results highlights once again that the design step is crucial for a successful ICCP system. The performance of a PCCI system is described in standard NF EN ISO 12696. From this work, it seems that the analysis of the resistances of the anode circuits as a function of time and temperature would provide interesting additional information on the evolution of the protected reinforced concrete without having to modify the monitoring system.

Acknowledgements

This study was part of the ACROBAT Project with funding from Comue Paris Est Sup in Marne-la-Vallée.

References

CEN/ISO (2022). *NF EN ISO 12696: Cathodic protection of steel in concrete*.

Bennett, J. and Turk, T. (1994). *Technical Alert : Criteria for the Cathodic Protection of Reinforced Concrete Bridge Elements* (SHRP-S-359). https://trid.trb.org/view/404929

Bouteiller, V., Damien, G., Boinski, F., Schneider, J. and Michaux, C. (2019). *Impressed current cathodic protection with embedded anodes – field trial on the Viaduc de Saint-Cloud in France.* Concrete Solutions 2019 – 7th International Conference on Concrete Repair, 289, 03002. https://doi.org/10.1051/matecconf/201928903002

Bouteiller, V., Jacquel, A., Damien, G., Boinski, F., Schneider, J. and Michaux, C. (2015). *Protection Cathodique par Courant Imposé à l’aide d’anodes forées—Chantier pilote du Viaduc de Saint-Cloud.* Bulletin Ouvrages d’Art, 73, 24-43.

Broomfield, J. P. (2006). *Corrosion of Steel in Concrete : Understanding, Investigation and Repair, Second Edition*. CRC Press.

Ducasse-Lapeyrusse, J., Bouteiller, V., Marie-Victoire, E., Bouichou, M., Damien, G., Martinet, V., Annede-Villeau, C. and Lesieutre, O. (2023). *Assessment of the Impressed Current Cathodic Protection system after 4 years operation : Case study of the Saint-Cloud Viaduct (France).* Case Studies in Construction Materials, 18, e02023. https://doi.org/10.1016/j.cscm.2023.e02023

Hunkeler, F. (1992, mai). *Cathodic Protection of the San Bernardino Tunnel -Installation and Results of a Field Study*. Cathodic Protection of Reinforcement in Concrete: Opportunity and Efficiency, Paris.

Mathivat, J. (1973). *Le nouveau pont de Saint-Cloud sur le prolongement de l’autoroute A13 de Saint-Cloud à Paris.* Travaux, 465, 39-52.

Pedeferri, P. (1996). *Cathodic protection and cathodic prevention.* Construction and Building Materials, 10(5), 391-402. https://doi.org/10.1016/0950-0618(95)00017-8

Pedeferri, P. (2018). *Cathodic and Anodic Protection.* In P. Pedeferri (Éd.), Corrosion Science and Engineering (p. 383-422). Springer International Publishing. https://doi.org/10.1007/978-3-319-97625-9_19

Polder, R. and Peelen, W. (2019). *Cathodic protection of reinforcement in concrete–experience and development over 30 years.* Concrete Solutions 2019 – 7th International Conference on Concrete Repair, 289, 03006. https://doi.org/10.1051/matecconf/201928903006

Sohanghpurwala, A. A. (2009). *Cathodic protection for life extension of existing reinforced concrete bridge elements* Numéro Project 20-5 (Topic 39-03). Transportation Research Board.

Wilson, K., Jawed, M. and Ngala, V. (2013). *The selection and use of cathodic protection systems for the repair of reinforced concrete structures.* Construction and Building Materials, 39, 19-25. https://doi.org/10.1016/j.conbuildmat.2012.05.037