State of the art on the calculation of anodic resistance for cathodic protection of steel in concrete

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Abstract. For the design of cathodic protection (**I**mpressed **C**urrent **C**athodic **P**rotection (**ICCP**) or **S**acrificial **A**node **C**athodic **P**rotection (**SACP**)) of steel in concrete using drilled-in discrete anodes, the rectifier output voltage and current are selected (for ICCP) based on a multi-criteria analysis (steel surface, concrete performances, results of material and corrosion diagnostics, oxygen availability, exposure to pollutants, expected service life, etc.). However, the rules for calculating anodic resistance (which makes a major contribution to overall circuit resistance) are not universally accepted in the profession, since the calculation rules used for cathodic protection of buried or immersed metal structures, which could be used by analogy, assume that the electrolyte is infinite, which cannot be the case in concrete. As a result, some designers are now skipping this fundamental step. Cumulative polarization measurements over the commissioning period have been carried out for several years on different projects, with different anode systems, and the results demonstrate consistency in the shape of the curves obtained and confirm the difficulty of assessing the contribution of the various parameters to be considered to enable the drafting of a robust and realistic limit state design hypothesis note. The final section concludes with the value of pilot testing in securing the design hypothesis.

1 Introduction / Purpose

This article reports on experience gained in the design of cathodic protection systems for steel in reinforced or prestressed concrete (engineering structures and/or buildings), particularly the design of cathodic protection systems using discrete drilled-in anodes in strings (chains).

- When designing and sizing cathodic protection for steel in concrete (in particular, the sizing of the anode circuit, not only in terms of the choice of anodes, but also the distribution of positive contacts for uniform distribution of the protective current, taking into account the voltage drop in the anode circuit), several standards or specialized articles can be used as bibliographical references (non-exhaustive list) by the engineer responsible for the project [1,2,3,4,5,6,7,8,9,10]. When following all these recommendations, the designer must take several aspects into account when deploying discrete embedded anodes:
- The theoretical number of anodes must be compared with the actual geometry of the structural element to be protected (presence of steel and maximum distance between anodes that must not be exceeded to avoid the risk of an under-polarized area),
- EN ISO 12696 (2022) is a performance standard that clearly defines the objectives and criteria to be achieved in order to qualify the effectiveness of cathodic protection systems, but no information is provided on how to calculate the distance between anodes or the anodic resistance (which nevertheless remains a major contributor to the calculation of voltage drop (including the identification of components as illustrated in Fig.1. below) in circuits (up to 85 to 90% depending on the case as illustrated in Fig.2. below)). Only the need for verification by a test site is mentioned.

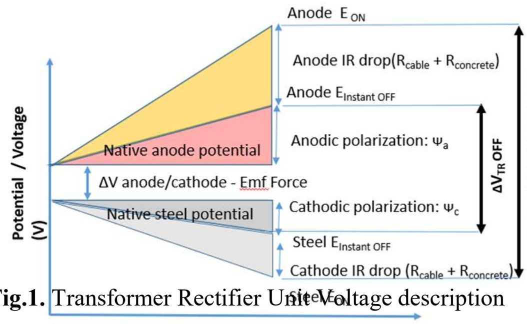

Fig.1. Transformer Rectifier Unit Voltage description

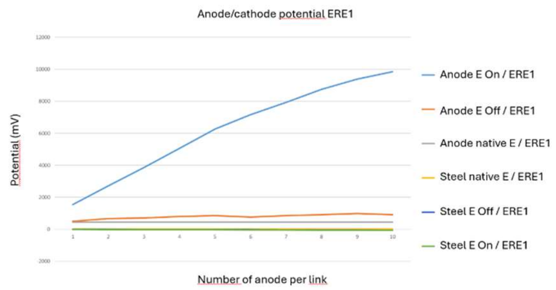

Fig.2. Illustration of the major contribution of anodic polarisation to the composition of tension output (ERE1 is a Mn/Mn0$_2$ reference cell permanently sealed in concrete).

In his design diagram (Refer to Fig.3. below) Professor Lazzari [3], discusses the calculation of the total circuit resistance $R_{tot} = R_a + R_c + R_{cable}$, followed by the calculation of the expected station voltage $U = I \times R_{tot} +$ UFCEM. Experience has shown that R_c (cathode circuit resistance) is usually negligible, and that the counter-electromotive force generally varies between 0.5 and 1.5volts DC.

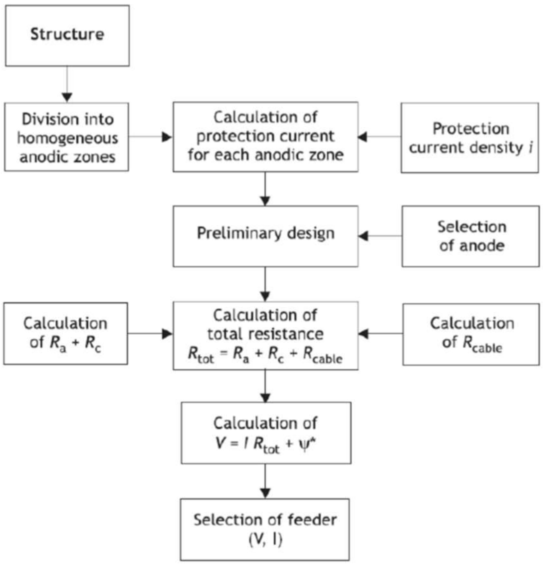

Fig.3. Cathodic protection design flowchart - Professor L Lazzari

Cable resistance is calculated using the following formula: R = (ρ x L)/S where ρ is the resistivity of the conductive metal, L is the length of the cable and S is the cross-sectional area of the cable. It is therefore still necessary to estimate Ra (anodic circuit resistance) to accurate rectifier ratings.

- To date, there are no commonly accepted rules for calculating the anodic resistance of reinforced (or prestressed) concrete, which poses a problem depending on the technology chosen:
- When the applied current is selected, many solve the problem empirically by choosing equipment that can distribute voltages between 0 to 24 Volts DC, or even higher in some specific cases.
- When sacrificial anodes are used, it is not uncommon to see designs based solely on a simplified calculation using Faraday's formula for theoretical mass consumption, but failure to take anodic resistance into account makes it more uncertain whether the effectiveness criteria will be met (which is why, for example, the 2022 version of standard EN ISO 12696 excludes anodes drilled around repairs for the reduction of anodes induced by the edge effect).

2 Feedback

It was during quality control checks, in particular the absence of short circuits during the implementation of ICCP on a prestressed concrete viaduct 10 years ago, through the unit polarization of each drilled-in anode before they were connected to form anodic chains (discrete drilled-in anodes 8 mm in diameter and 170 mm in active length, for chains ranging from 10 to 25 units), it was verified that the overall resistance of the circuit decreased systematically and repeatedly as the number of anodes with the same profile (Refer to Fig.4. below) increased, regardless of the section tested. This initial observation led to multiple additional checks, which confirmed the logarithmic decrease trend, as illustrated by the curves following.

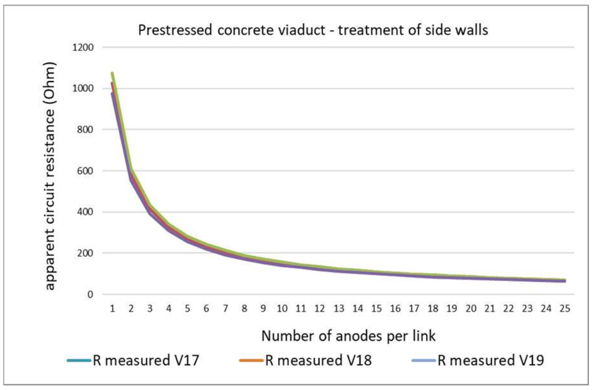

Fig.4. Measured anodic resistance curves on 3 segments

This raised the first question:

- Which formula for calculating anodic resistance can be used as a reference? The formulas used to calculate anodic resistance for buried or submerged metal structures (which are most similar to concrete structures) are based on the assumption that the medium is infinite, which by definition cannot be the case in reinforced concrete, where the maximum distance between the anodes and the steel to be protected is generally accepted to be around 35 cm and the distance between the anodes is usually kept to less than or equal to 50 cm, with the distribution of the ionic current flow being influenced by the geometry of the structure, the concrete cover and the presence (or not) of a protective coating and, above all, by high or very high resistivity depending on the case (deeply carbonated concrete, etc.).
- Should the diameter of the anode or the diameter of the drilled hole be considered in the calculation?
- What is the impact of the geometric parameters of the anode?
- What is the impact of the spacing between the anodes?
- Etc.

3 Site measurements

Thus, for the past 10 years, with the aim of acquiring several representative measurements and cases of the various possible situations (all proportions and measurements combined), during on-site quality controls during the implementation of cathodic protection systems for steel in concrete, cumulative anodic polarizations (Refer to Fig.5. below) have been performed when connecting the anodes to form anodic chains to create a statistical data set on the behaviour of the anodic systems in order to detect any 'abnormal' one, given that 500 voussoirs had to be processed in each direction of traffic. To compare all things being equal, the following elements have been systematically retained:

- Consider that the overall resistance of the circuit (excluding the connector) is calculated according to the following formula (Refer to formula (1) below):

$$R_{CPcircuit} = \frac{\Delta VTR_{ON} - \Delta VT\ \ _{OFF}}{I} \qquad (1)$$

with negligible cathodic resistance compared to the anodic resistance (considering the total surface area of the reinforcement in the area affected by cathodic protection and the verification measurements carried out on site),

- Connect the discrete drilled-in anodes to an anode cable of a predefined final length so that the linear resistance R_{cable} is constant. On this basis, the assessment of the expected lifetime of the zinc sacrificial anodes in concrete was carried out by applying Faraday's law to determine the mass of zinc, as a function of the protection current density supplied by the anode during a given period.

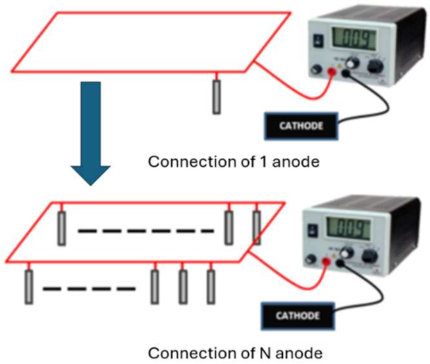

Fig.5. Wiring principle of the anode circuit for cumulative polarisation.

- Measure the voltage across a calibrated 1 Ω shunt connected in series using a high impedance calibrated digital voltmeter to ensure accurate evaluation of the current dissipated.
- Perform measurements at steady current over a short interval (3 seconds max), followed by a period without current for at least 10 seconds, to avoid drifting in the measurement acquisition due to residual cathodic polarization,
- For systems with imposed current, impose a unit anodic current density corresponding to an anodic current density of 110 mA/m² of anode,
- Perform cumulative polarization by connecting the anodes one by one and imposing the design current density corresponding to the number of connected anodes,
- Consider that the variability of the overall circuit resistance corresponds to the contribution of the additional anode (for SACP, the same principle was adopted, with the difference that no current was imposed but the voltage and current flow were evaluated simultaneously and systematically).

These measurements confirmed that the number of anodes appears to be a major contributor to the decrease in circuit resistance, regardless of the anodes, their shape and size, the resistivity of the concrete and the type of cathodic protection (ICCP or SACP): the curves all have the same shape (Refer to Fig.4 before), with a pseudo-horizontal asymptote from the 15th anode onwards... which is predictable behaviour for parallel anodes, but not documented for reinforced concrete.

4 Comparison with methods for calculating anodic resistance

Dwight's formula, commonly used in the land sector, is well suited to a single vertical anode (Refer to formula (2) below, by analogy with a discrete drilled-in anode in the concrete/outer surface from which it is implemented).

$$R = \frac{\rho}{2\pi L} (\ln (\frac{4L}{d})\text{-}1) \qquad (2)$$

To account for the interaction between anodes, it was decided to use Dwight's formula, supplemented by a grouping factor (Refer to formula (3) and (4) also known as the anodic interaction factor), bearing in mind that in the land sector.

This leads to the corrected equation below:

$$R_N = \frac{R_1}{N \cdot F_g} \quad (3) \qquad \text{with } F_g = \frac{1}{1 + a(N-1) \cdot \frac{L}{S}} \quad (4)$$

The aim is to incorporate the influence of the spacing between anodes on mutual interference into the calculation. The formula was incorporated into an interactive spreadsheet to compare the theoretical results obtained by its application with the results in the field, using the following parameters:

N = number of anodes connected in the anodic circuit.
$R_{(N)}$ = apparent circuit resistance (Ω)
ρ = concrete resistivity (Ωm)
L = anode length (m)
d = diameter of the hole for placing the anode (m)
Fg = interaction coefficient between the anodes
S = distance between the anodes (m)

The Fg coefficient was established for a correspondence of resistance values between anodes 15 and 25. Reminder: the comparison cannot be made directly in absolute values, as the values measured directly on site are apparent circuit resistance values. A correction coefficient of 15% has therefore been used in the spreadsheet calculations.

By comparing the simulation results with the measurements taken on site, it became apparent that the formula needed to be corrected: the presence of the L/S ratio creates an inflection point that is unfavorable to the parallelism of the two curves and influences the value of the ordinate. It was therefore decided to carry out the comparison while keeping the grouping factor constant because:

- the curves plotted from the measurements confirmed a low slope that decreases after the 15th anode, indicating that adding an additional anode contributes proportionally less to the reduction in overall anodic resistance than the previous one.

- the spacing between the anodes in the concrete is mainly determined by the resistivity of the concrete and the presence of reinforcing steel, and apart from large construction sites where the number of anodes has a significant impact on the budget, for construction sites with a small number of anodes, the contribution of the number of units to be used is not significant.

5 Measurements on short anodes – ICCP:

In this section, several cases are studied for anodes of different shapes and lengths ranging from 17 to 45 cm, in different environments:

Case 1: Implementation of ICCP on the side beams of a prestressed viaduct built between 1972 and 1974 (Refer to Fig.6. below).

Anodes: cylindrical TiMMO ribbon anodes with a diameter of 8 mm

N = 25 anodes
L = 170 mm is the length of the anode
d = 16 mm is the drilled hole diameter
ρ = resistivity of the concrete as defined in the consultation documents = 200 Ω.m
S = 500 mm

Fig.6. Sloping side veil of the front viaduct deck after preparation of the substrate by hydro demolition

For each segment, the measurements taken on site were compared with the results obtained using the calculation formula defined above, with a constant Fg coefficient, based on values between the 15th and 25th anodes.

Segment 17: ρ = optimized resistivity = 225 Ω.m
Fg = 0,3 a match between N=15 and 25 units
Segment 18: ρ = optimized resistivity = 215 Ω.m
Fg = 0,27 a match between N=15 and 25 units
Segment 19: ρ = optimized resistivity = 210Ω.m
Fg = 0,29 a match between N=15 and 25 units

The most accurate assessment of the results of the calculation, based on a comparison of the apparent circuit resistance values measured according to the number of anodes on the chain, leads to a correction coefficient Fg for segment no. 19 (as an example), with values ranging from 0.47 for N=1 to 0.29 for N=25 anodes (Refer to Fig.7. below).

NB: This assessment is only possible with:

- a factual assessment of the resistivity of the concrete using cores taken on site (because estimating the skin resistivity using a 4-point measurement is not representative of the concrete at depth, particularly in the presence of high steel density),
- a sufficient number of cores taken, because an estimate based on an insufficient number of samples leads to results that are unreliable and unrepresentative of reality, with differences in the intrinsic characteristics of the concrete and the resulting consequences that must be assessed during the construction phase, which can prove problematic both in terms of schedule and technical issues (with the possibility of the initially planned anodic system having to be reconsidered).

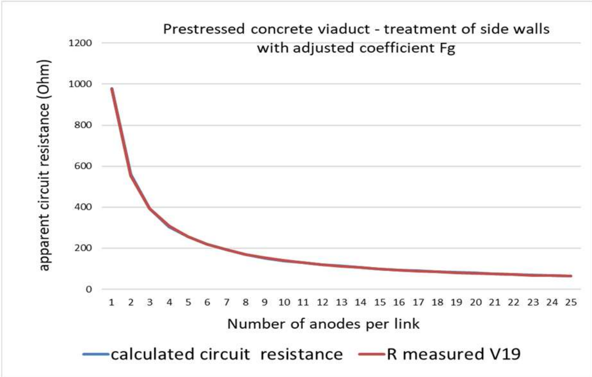

Fig.7. Resistance of the anodic circuit on segment 19 with modified Fg coefficient

This comparison with the variable Fg coefficient allows the curves to be perfectly aligned but is not relevant for the final evaluation that will be incorporated into the rectifier design.

Case study 2: implementation of ICCP on heavily carbonated old concrete on vertical columns of a reinforced concrete tower built in 1924 (Refer to Fig.8. below).

Anodes: 6-branch TiMMO star anodes in 19 mm diameter ribbon

N = 24 anodes
L = 350 mm is the length of the anode
d = 28 mm is the drilled hole diameter
ρ = resistivity is not precisely known but is estimated in a diagnostic report prior to the work phase to be between 500 and over 3500 Ω.m.
S = 400 mm

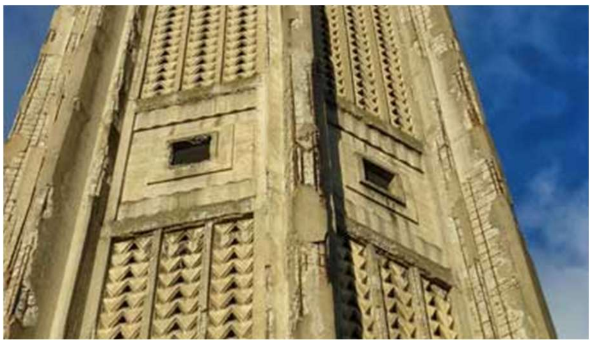

Fig.8. Concrete tower before repair work begins

Using the spreadsheet gives the following results:

Pilar B: ρ = optimized resistivity = 605 Ω.m
Fg = 0,32 a match between N=15 and 25 units
Pilar D: ρ = optimized resistivity = 610 Ω.m
Fg = 0,34 a match between N=15 and 25 units

As with the previous project, comparison between the calculation results and field measurements confirmed a change in the Fg coefficient depending on the number of anodes, with the two curves converging from the 15th anode onwards (Refer to Fig.9. Below)

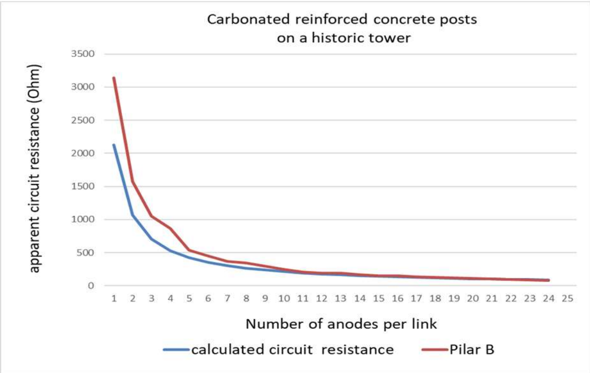

Fig.9. Resistance of the anodic circuit on pilar B

Case 3: Reinforced concrete segments in a tunnel built in 2008, exposed to de-icing salt (Refer to Fig.10. below)

Anodes: 6-branch TiMMO star anodes in 19 mm diameter ribbon
N = 30 anodes
L = 350 mm is the length of the anode
d = 25 mm is the drilled hole diameter
ρ = unknown resistivity
S = 350 mm

Fig.10. Pilot test in the tunnel ventilation gallery

Using the spreadsheet gives the following results: segments 71 to 73 North tube

ρ = calculated resistivity = 315 Ω.m and Fg = 0.3
It should be noted that the fit between the measured curves and the theoretical curves is more accurate than in the first two cases with a constant adjustment coefficient (Refer to Fig.11. below).

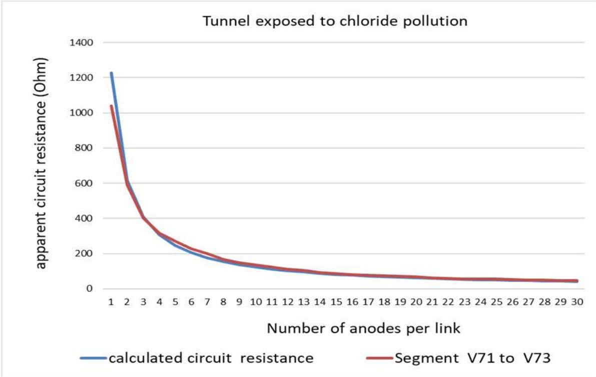

Fig.11. Resistance of the anodic circuit on segments 71 to 73

Case 4: Implementation of ICCP on the side beams of a motorway overpass built in 1970 (Refer to Fig.12. below).

N = 29 anodes,
L= 450 mm is the length of the anode for lateral beam
d = 25 mm is the drilled hole diameter
ρ = unknown resistivity
S = 400 mm

Fig.12. Installation of discrete drilled-in anodes on the downstream side beam of the deck

The calculation yields the following results for the downstream edge beam in direction 2: ρ = optimized resistivity = 175 Ω.m with Fg = 0.32 (Refer to Fig.13. below).

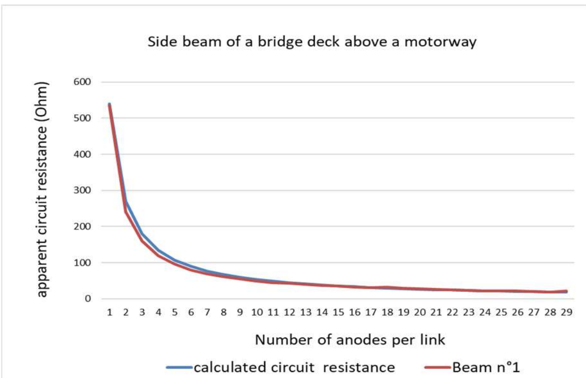

Fig.13. Resistance of the anodic circuit for 29 TiMMO discrete drilled-in anodes on lateral beam

Case study 5: implementation of ICCP on the head beams of the abutments of a motorway overpass built in 1970 (Refer to Fig.14. below).

Anodes: 6-branch TiMMO star anodes in 19 mm diameter ribbon
N = 30 anodes,
L= 600 mm is the length of the anode
d = 25 mm is the drill hole diameter
ρ = unknown resistivity
S = 600 mm

Fig.14. Treatment of the head beam on the abutment using discrete 600 mm drilled-in anodes

The calculation yields the following results for the header at the head of abutment C2: ρ = optimized resistivity = 235 Ω.m with Fg = 0.14

Observation: beyond the differences in the intrinsic characteristics of the concrete (chloride-contaminated concrete for the engineering structures and carbonated concrete without chlorides for the 1925 tower, with the resulting variability in resistivity) and the mechanical performance of the concrete in place: field measurements show consistent behaviour for the 35 cm anodes, and the two subsequent series confirm the significant contribution of anode length to the final anodic resistance value (Refer to Fig.15. below).

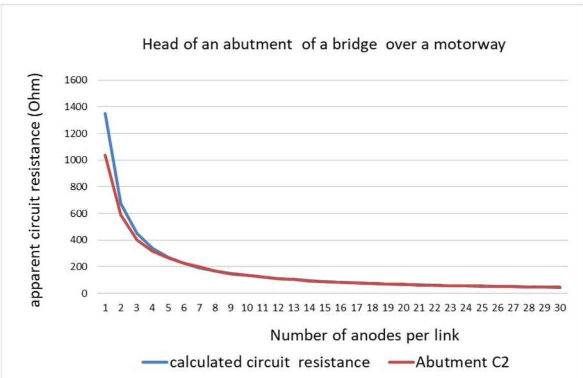

Fig.15. Resistance of the anodic circuit for 30 TiMMO discrete drilled-in anodes

6 Measurements on long anodes - ICCP & SACP

In this section, several cases are studied for anodes of different shapes and lengths between 95 and 100 cm, whether TiMMO anodes or Zinc anodes of different profiles, in different environments:

Case 6: implementation of ICCP on the abutments of a motorway overpass built in 1985 (Refer to Fig.16. below).

Anodes: 6-branch TiMMO star anodes in 19 mm diameter ribbon
N = 25 anodes
L = 950 mm is the length of the anode
d = 32 mm is the drill hole diameter
ρ = unknown resistivity
S = 500 mm

Fig.16. Treatment of the abutment using TiMMO discrete 950 mm drilled-in anodes

The calculation yields the following results:
Top line (LH): ρ = optimised resistivity = 70 Ω.m, with Fg = 0.59
Medium line (LM): ρ = optimised resistivity = 110 Ω.m, with Fg = 0.7
Low Line (LB): ρ = optimised resistivity = 120 Ω.m with Fg = 0.72

In this example, unlike the previous cases, an adjustment with a constant correction coefficient is not possible. Furthermore, an increase in the calculated resistivity is observed as a function of the height of the anode line, which corresponds to the difference in exposure to de-icing salts, with the upper surface of the threshold beam being the most exposed to direct runoff from the road joints. The Fg coefficient was taken following the observation that the two curves converged from the 15th anode onwards (Refer to Fig.17. below for anode top line).

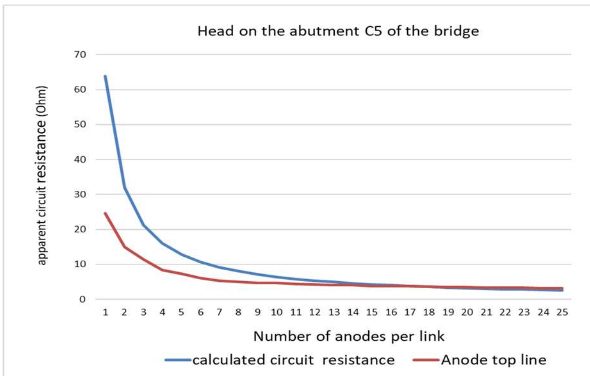

Fig.17. Resistance of the anodic circuit for 25 TiMMO discrete drilled-in anodes

Case 7: SACP treatment of steel on the upper surface of a lintel on the abutment of a motorway overpass built in 1970 (Refer to Fig.18. below).

Anodes: pre-coated zinc anodes

N = 19 anodes
L = 950 mm is the length of the anode
d = 50 mm is the drill hole diameter
ρ = unknown resistivity
S = 500 mm

Fig.18. Treatment of the abutment using discrete Zinc 95 cm drilled-in anodes

The calculation yields the following results for the line of 19 anodes on C1: ρ = optimised resistivity = 210 Ω.m, Fg = 0.6. There is a close relationship between the two curves, with a constant Fg coefficient (Refer to Fig.19. below).

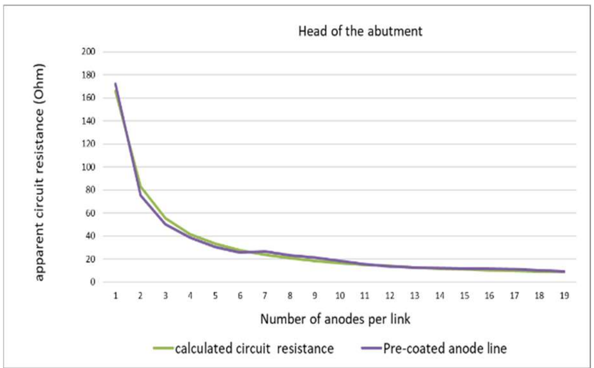

Fig.19. Resistance of the anodic circuit for 19 discrete Zinc drilled-in anodes

Case 8: Treatment of extrados steel using SACP on two stringers on the abutment of a motorway overpass built in the 1980s

Anodes: drilled-in zinc anodes sealed on site with activation mortar (Refer to Fig.20. below)
N = 26 anodes
L = 950 mm is the length of the anode
d = 32 mm is the borehole diameter
ρ = unknown resistivity
S = 500 mm

Fig.20. Discrete Zinc drilled-in anodes to be be sealed on site with activation mortar

The calculation yields the following results:
Abutment No. 1: ρ = optimized resistivity = 206 Ω.m and Fg = 1.2, with good correlation between the curves, despite the dispersion in the field measurements. (Refer to Fig.21. Below)

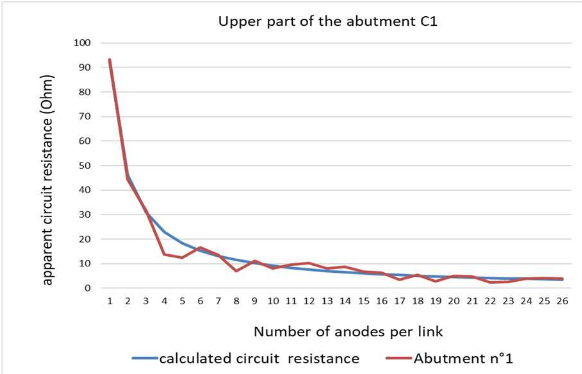

Fig.21. Resistance of the anodic circuit for 26 Zinc discrete drilled-in anodes - abutment n°1

Abutment No. 2: ρ = optimized resistivity = 172 Ω.m and Fg = 1.5 with significant correlation between the two curves (Refer to Fig.22. below).

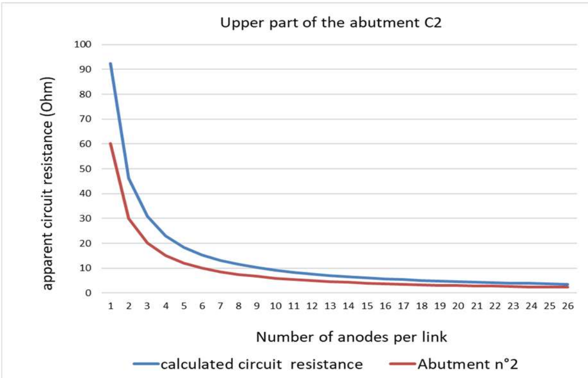

Fig.22. Resistance of the anodic circuit for 26 Zinc discrete drilled-in anodes- abutment n°2

Observation: as with the 35 cm anodes, beyond the differences in the intrinsic characteristics of the concrete, field measurements show consistent behaviour for anodes between 95 cm and 1 metre in length, starting from the 15th unit, as for the previous ones. It should be noted that pre-coated anodes (sacrificial anodes whose sacrificial alloy activation mortar is applied in the factory, as opposed to anodes sealed directly on site, where the sealing mortar also acts as the activation mortar) appear to offer greater resistance than anodes sealed directly on site with an activating mortar.

Case 9: Installation of discrete drilled-in zinc sacrificial anodes around the repair area on the

underside of a cantilevered section of a prestressed motorway viaduct (Refer to Fig.23. below).

Anodes: zinc anodes sealed on site
N = 30 anodes
L = 82 mm is the length of the anode
d = 25 mm is the drill diameter
ρ = unknown resistivity
S = 400 mm

Fig.23. Installation of discrete drilled anodes around repairs

Using the spreadsheet gives the following results: ρ = optimised resistivity = 100 Ω.m and Fg = 0.3 5 (Refer to Fig.24. below).

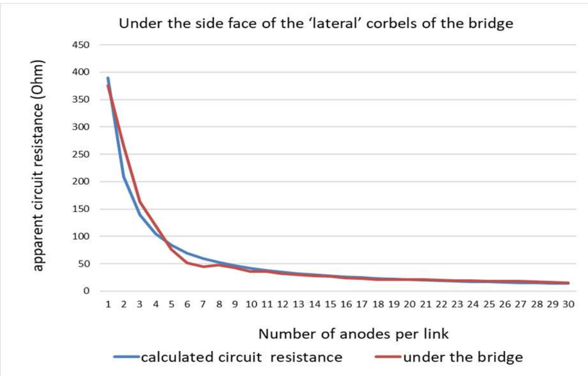

Fig.24. Resistance of the anodic circuit for 30 Zinc discrete drilled anodes around repairs

7 Conclusion

The on-site measurements and calculated values revealed several elements:

1. Regardless of the shape of the anodes (circular, star-shaped, etc.), their length and the characteristics of the concrete, the curves show the same pattern: a logarithmic reduction with, from 15 drilled in anodes onwards, a pseudo-horizontal asymptotic trend. (A comparison with the trend curves in Excel gives formulas with negative exponents, but the decision to keep a natural logarithm expression was made for consistency with the Dwight formula (2) initially used as a model.)

2. The Dwight formula weighted by an interference coefficient (3 & 4) between the anodes can be used to anticipate the behaviour of cathodic protection systems versus environmental conditions (variations in temperature, humidity, seasonality, etc., and therefore in the resistivity of the concrete), provided that this has been qualified during the pilot test by measurements on cores (measurements that are more representative than apparent surface resistivity measurements, except in the case of a single steel bed to be protected with short, and therefore shallow, drilled anodes).

3. This behaviour must be considered, for SACP systems for which the Fe/Zn potential difference is not adjustable, and for which the anodic resistance will contribute much more to the systems' ability to polarise steel than for ICCP systems for which the driving voltage is adjustable.

4. The shape of the anodic resistance curves provides information on the minimum number of anodes in the chain that should be aimed for to optimise the operation of cathodic protection systems and adds an additional parameter to the considerations that should lead to the design of the anode wiring.

5. The length of the anodes, regardless of the technology used (SACP or ICCP), appears to be a factor that contributes significantly to anodic resistance, even more so than the number of anodes in the string, and even before the resistivity of the concrete, as shown in the two summary tables above (Refer to Fig.25. and Fig.26. below).

Anodic circuit resistance measured on site (Ω)						
Structure type	Case n°1 - Prestressed concrete viaduct			Case n°2 - Historic Tower		Case n°3 - Tunnel exposed chloride
Anodic Zone	Z17	Z18	Z19	reinforced concrete post D	reinforced concrete post B	Segment 71 to 73
Anode Lenght	170 mm	170 mm	170 mm	350 mm	350 mm	350 mm
1	1025	1075	975	1515	3140	1039
14	111	117	105	136	167	93
15	105	110	99	127	151	88
16	99	104	94	121	148	82
17	94	99	89	114	136	78
18	89	94	85	106	130	74
19	85	89	81	102	121	71
20	82	86	78	99	113	68
21	78	82	74	97	104	62
22	75	78	71	94	95	60
23	72	76	68	92	89	57
24	69	73	66	89	81	55
25	67	70	64	85		55

Fig.25. Anodic circuit resistance for short anodes in different concretes

Anodic circuit resistance measured on site (Ω)						
Structure type	Case n°6			Case n°7	Case n°8	
Anodic Zone	Top Line	Medium Line	Low line	Abutment C1	Abutment C1	Abutment C2
Anode Lenght	950 mm	950 mm	950 mm	1000 mmm	1000 mmm	1000 mmm
1	25	34	36	172	93	60
2	15	19	23	75	45	30
3	11	17	20	50	32	20
4	8	12	16	38	14	15
5	7	9	13	30	12	12
6	6	10	12	25	17	10
7	5	9	10	26	14	9
8	5	7	9	23	7	8
9	5	7	8	21	11	7
10	5	6	8	18	8	6
11	4	6	7	16	10	5
12	4	6	7	14	10	5
13	4	5	6	13	8	5
14	4	5	6	12	9	4
15	4	5	6	12	7	4
16	4	5	6	12	6	4
17	4	5	4	11	3	4
18	4	4	4	10	5	3
19	4	4	4	9	3	3
20	3	4	4		5	3
21	3	4	4		5	3
22	3	4	4		3	3
23	3	4	4		3	3
24	3	4	4		4	3
25	3	4	4		4	2
26					4	2

Fig.26. Anodic circuit resistance for long anodes in different concretes

6. The latest measurements taken on sacrificial anodes intended to reduce anodic processes induced by edge effects around repairs confirm the same trend, with significant circuit resistance despite relatively average concrete resistivity (concrete contaminated by chlorides over many years), most likely linked to the short length of the anodes. This last factor should be considered in the design, as it complement simply applying Faraday's law is not sufficient to determine the actual capacity of galvanic anodes to supply current: the variability over time of the anodic resistance depending on changes in the environment near the anode (half-life of the anode, changes in the chemistry of the zinc coating mortar [11,12], acid concentration at the anode leading to a drop in pH, etc.) must be taken into account.

7. The modified Dwight formula referred to in this work is not and will not be the only one possible. Furthermore, the comparison method based on the 15th anode is currently a simplified, pragmatic method used as part of an approach to improve the reliability of the design hypothesis note by using facts specific to the project concerned.

8 References

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