A simplistic method for the assessment of anode spacing and predicted life for galvanic point source anodes for atmospherically exposed steel in concrete

Cathodic protection has been proven as an effective and efficient method of preventing corrosion related deterioration of atmospherically exposed steel in concrete.

In recent years, the use of embedded galvanic anodes has increasingly been adopted as a cost effective and simple method for providing life extension to concrete patch repairs, providing cathodic protection to undamaged chloride contaminated concrete away from patch repairs and as a corrosion prevention method at new build.

Determining the spacing and theoretical life of embedded galvanic anodes in concrete is an essential skill which will enable the user to identify the minimum anode to anode spacing and predict the expected life of the embedded anode system.

The techniques and methods presented within this paper are based on a standardise approach which has been used successfully for designing galvanic anodes for sea water and soil application.

It is noted that concrete presents a number of other factors which may influence the overall performance of embedded anodes, such as changing concrete resistivity, oxygen diffusion, passive film formation, concrete pore blocking, the solubility and mobility of anode corrosion products etc. These factors have not been considered within this paper and will require further investigation and evaluation in conjunction with the procedures presented herein.

The calculation process is divided into a number of different stages as follows:

Stage 1 - steel surface areas or steel density calculations

Stage 2 - design current density and cathode (steel) current demand

Stage 3 - theoretical and actual anode capacity, based on anode mass, utilisation factor and efficiency

Stage 4 - total cathode current demand based on design life.

Stage 5 - number of anodes required based on the actual anode capacity and total cathode demand over the design life.

Stage 6 - calculating anode resistance for individual and clustered anodes

Stage 7 - determining the anode to cathode driving voltage

Stage 8 - calculating anode current based on anode resistance and driving voltage

Stage 9 - current demand vs anode current supply check

Stage 10 - anode interference factor & effect on anode quantity

Stage 11 - anode spacing based on selected number of anodes

Stage 12 - expected voltage shift at ½ the anode spacing

Stage 13 expected anode life based on anode selection

Stage 1 – Cathode surface area or steel density

Determination of the cathode surface area is required for calculating the cathode current demand or how much energy is required to stop or control the corrosion process.

The reinforcement steel density requires knowledge of the reinforcement diameter and the reinforcement spacing, this information can be found on as-built drawings and/or determined on site, using a combination of cover survey and exploratory break out to expose the reinforcement and enable measurement to be undertaken.

The reinforcement diameter and spacing is then used to determine the amount of steel within 1m^2 of concrete using the following formula.

Sd= N x L x D x π

Sd – steel density (m^2)

N – number of bars within 1 m (normally 1m/ bar spacing in m)

L – bar length (m)

D – bar diameter (m)

π – is a mathematical constant the ratio of a circle's circumference to its diameter 3.14159

This formula needs to be used for each bar diameter and each bar in the longitudinal and transvers directions.

For example:

A single layer reinforcing mat, consisting of 32mm dimeter bars at 0.25m centres in the longitudinal direction and 25mm diameter bars at 0.25m centres in the transvers direction will require the following calculation based on a 1m^2 grid.

Steel density = number of bars in 1m x the bar length x the bar diameter x π

Sd1= 1/0.25 x 1m x 0.032 x π = 0.402m2 steel per m^2 concrete, for the 32mm bars

Sd2= 1/0.25 x 1m x 0.025 x π = 0.314m2 steel per m^2 concrete, for the 25mm bars

St - the total steel density within 1m^2 of concrete

is then

St = Sd1 + Sd2

= 0.402 + 0.314

= 0.716m^2 steel per m^2 of concrete (1)

This procedure is then expanded for different steel density areas containing different bar diameters and bar spacings on the structure, for example bar overlap areas, starter bars and is also applicable for multiple layers or mats of reinforcement.

St = Sd1+Sd2+Sd3+Sd4….

Stage 2 – Cathode current demand

The cathode current demand, or how much energy is required to stop or control the corrosion process, is based on the use of current densities which have been determined experimentally, against varying levels of chloride contamination and the state of the reinforcement i.e passivity or the different stages of pitting corrosion.

International standards like ISO 12696 identify a range of design current densities which may be used to calculate the current demand for atmospherically exposed reinforced concrete as follows:

- For cathodic protection of atmospherically exposed concrete, a design current density of 2mA/m^2 to 20mA/m^2 steel is required
- For cathodic prevention of atmospherically exposed concrete, a design current density of 0.2mA/m^2 to 2mA/m^2 steel is required

The selection of the design current density is directly affected by the degree of chloride contamination, which in turn affects the stability of the passive layer and degree of corrosion.

The following table identifies the minimum design current density and polarisation required to achieve a corrosion rate of 0.0025mm/y for different chloride levels.

Cl^- wt% cement	CP current needed mA/m^2	Polarisation needed mV
<0.2	0	0
0.2 - 0.3	5.38	60
0.3 - 0.8	11.84	80
0.8 - 1.6	17.2	100
>1.6	>17.2	150
Bennett & Bromfield 1997 Analysis of studies on cathodic protection criteria for steel in concrete,		

The international standards on cathodic protection provide little guidance on selecting design current densities, for achieving cathodic protection.

The following scenarios are presented as examples to demonstrate the design process and philosophy, identifying items to consider when selecting design current densities.

Scenario one

A structure which has significant chloride contamination, greater than 1.6wt% Cl^- per wt of cement, has significant rust staining, but limited cracking and spalling (little to no concrete repairs) a current density of 15-20mA/m^2 steel may be selected, using the above table and according to ISO 12696 which lists the maximum design current density of 20mA/m^2 for cathodic protection.

This is due to the fact, that significant areas of the embedded reinforcement are actively corroding, and these areas will not be removed or repaired during the concrete repair process. The cathodic protection system will then need to deliver enough current (energy) to stop ongoing corrosion within active pits as these areas remain in undamaged chloride contaminated concrete.

Scenario two

A structure which has significant chloride contamination, up to 0.6wt% Cl^- per wt of cement, which has no rust staining, but significant cracking and spalling (lots of concrete repairs) a current density of 5.38-11.84mA/m^2 steel may be selected from the above table.

This is due to the fact, that significant areas of the embedded reinforcement which are actively corroding will be exposed during the concrete repair process, the reinforcement cleaned, and these existing anodic areas will be re-passivated within the new concrete repair material prior to the application of cathodic protection. Under these conditions the cathodic protection system will not need to stop active corrosion but only prevent the formation of concentration cell corrosion within the old contaminated concrete adjacent to the concrete repairs and provide cathodic prevention to passive steel in old contaminated concrete away from patch repairs.

Scenario three

A structure which has moderate chloride contamination 0.2-0.3wt% Cl^- per wt of cement at selected hotspot locations, (coinciding with leakage) which has no rust staining, but some cracking and spalling (localised concrete repairs) a current density of 0.2 – 5.38mA/m^2 steel may be selected, using the above table and according to ISO 12696 which lists the minimum design current density of 0.2mA/m^2 for cathodic prevention

This is due to the fact that the embedded reinforcement areas which are actively corroding will be exposed during the concrete repair process and these existing anodic areas will be re-passivated within the concrete repair material prior to the application of cathodic protection. Under these conditions the cathodic protection system will not need to stop active corrosion, but only prevent the formation of concentration cell corrosion within the old concrete adjacent to the concrete repairs and provide cathodic prevention to passive steel in old contaminated concrete away from patch repairs.

The current demand is then calculated using a selected design current density and the steel density determined in stage one as follow:

Cd= Sdt x dc

Cd – cathode current demand (Ay/m^2)

Sdt – total steel density for a 1m^2 concrete area from (1) (m2 steel /m^2 concrete)

dc – design current selected form the international standards (A/m^2)

For the following example, scenario 3 has been selected, with a maximum design current density of 5.38mA/m^2 steel, to determine the cathode current demand.

1st - convert the design current density from mA to Amp (divide by 1000)

Cd = Sdt (0.716m^2 steel per m2 of concrete) x dc (0.00538A)

Cd = 0.00385Ay/m^2 concrete (2)

A minimum current of 0.00385A (3.85mA) is required for every m^2 of concrete to provide cathodic protection for a single mat of reinforcement as detailed in stage 1, under conditions described in scenario 3.

This procedure can then be expanded for:

- different steel density areas containing different steel diameters and bar spacings
- different design current densities based on existing chloride levels and repair scenarios.

Note - Applying cathodic protection current to the steel surface makes the steel negatively charged, which causes the negatively charged chloride (Cl^-) ions to migrate away from the steel surface, effectively reducing the Cl^- ion concentration with time.

The applied cathodic protection current, leads to the generation of hydroxide ions (OH^-) on the steel surface, effectively increasing the OH^- ion concentration with time.

This combined reduction of Cl^- ions and increase of OH^- ions, leads to a reduction of the chloride to hydroxide ion (Cl^-/OH^-) ratio at the steel surfaces, which is responsible for passive film stability. At levels > 0.6 Cl^-/OH^- corrosion pit initiation, pit stabilisation and pit propagation occurs at levels < 0.6 Cl^-/OH^- passive film stabilisation and corrosion prevention occurs.

As detailed in table 1, the current density required to prevent corrosion of steel in concrete is directly related to the chloride concentration at the steel, any reduction of the chloride levels, effectively reduces the design current density required to stop and prevent corrosion. As a result of this phenomenon, the design current density required to achieve cathodic protection, reduces with time and the initial design current density used for design purposes should be considered as conservative.

Under scenario 3 conditions, to account for this reduction of current demand with time, an alternative approach can be used, to calculate the required current demand. Based on the maximum design current density for an initial period, associated with stopping corrosion, a reduced design current density for the secondary period of passive film healing and a maintenance current density for the final period of cathodic prevention following passive film stabilisation.

- Phase 1 - Initial high current density, required for stopping corrosion at maximum chloride levels (for 0.2-0.3Wt%Cl-, a design current density of 5.38 mA/m^2 is required for 1 year).
- Phase 2 - Reduced current density required 75 % of original design current density, required for healing the passive film following reduction of chloride levels at the steel surface. (for 0.2-0.3Wt%Cl-, a design current density of 4.035 mA/m^2 is required for 1 year).
- Phase 3 - Maintenance or cathodic prevention current density, following passive film stabilisation, required to prevent pit initiation and pit stabilisation (2 mA/m^2 for the remaining life, based on the maximum current density listed within ISO 12696 for cathodic prevention).

Using the approach detailed above, the individual current demand of each phase can now be calculated.

Cd phase 1 = Sdt (0.716m2 steel per m^2 of concrete) x dc (0.00538A) = 0.00385 Ay/m^2 concrete (2a)

Cd phase 2 = Sdt (0.716m2 steel per m^2 of concrete) x dc (0.004035A) = 0.00289 Ay/m^2 concrete (2b)

Cd phase 3 = Sdt (0.716m2 steel per m^2 of concrete) x dc (0.002A) = 0.001432 Ay/m^2 concrete (2c)

Stage 3 – Theoretical and available anode capacity

Embedded galvanic anodes for atmospherically exposed concrete are typically fabricated from pure zinc.

The principal of galvanic cathodic protection is that as the metallic zinc corrodes, it produces energy which can be used for cathodic protection purposes.

The following chemical reaction identifies that a single atom of zinc releases 2 electrons (energy).

$Zn \rightarrow Zn^{2+} + 2e^{-}$

Faradays law allows us to determine the amount of energy a given mass of metal can provide, as a result of the corrosion process, which is based on the number of electrons (energy) transferred.

$$Q = \frac{nFm}{M}$$

Q = Charge (Coulomb or Amp per second)

n = Number of electrons transferred

F = Faradays constant (96500 C/mole)

m = mass of metal oxidised (g)

M = atomic weight of metal (g/mole)

Using the periodic table, it is possible to identify the atomic weight of zinc (65.39 g/Mol) and from the manufacturers of the anodes we can obtain the anode mass, (e.g. a zinc layer roll anode has a zinc mass of 61g per anode).

Using the above formula, it is now possible to calculate the available charge (energy) per anode.

$$\text{Charge (energy) } Q = \frac{2 \times 96500 \times 61}{65.39}$$

$$Q = 180042.82 \text{ C or A.s}$$

To determine the amount of current available in a 1 year period the result is divided by the number of seconds in a year as follows:

Nsy – number of seconds in a year

Nsy= 60s per minute x 60 minute per hour x 24 hour per day x 365 days per year

Nsy = 31536000 s

The theoretical anode capacity is then determined for a 1 year period using

Tc = Q/Nsy

Tc -Theoretical anode capacity at 100% (A.y)

$$Tc = 180042.82 \text{ A.s} / 31536000\text{s}$$

$$Tc = 0.0057 \text{ A.y or } 5.7\text{mA.y per anode} \qquad (3)$$

The theoretical anode capacity assumes that all of the anode mass is converted into energy, in practice this is not the case and two factors need to be considered,

- The anode efficiency (ξ)
- The anode utilisation (μ)

Anode efficiency is related to the ability of the material to convert metal loss into available energy. Some of the theoretical capacity or energy may be used up during the corrosion process and will not be available for cathodic protection applications. To address this issue an anode efficiency of zinc in concrete of 80 % has been selected, this means that only 80% of the theoretical anode capacity is available to provide cathodic protection current and the other 20 % will be lost during the corrosion process.

Anode utilisation is related to the fabrication and consumption of the anode. Anode consumption may not be uniform and at some point, the main current carrying element of the anode may be compromised, preventing further current transport. For the roll anodes a utilisation factor of 90 % has been selected, this means that 90% of the anode will be consumed prior to any impact on current transport.

The anode efficiency and anode utilisation factors have a direct impact on the theoretical anode capacity and the actual anode capacity or energy available for cathodic protection can be determined as follows:

$Ac = Tc \times \xi \times \mu$

Ac - Available anode capacity A.y per anode

ξ - Anode efficiency

μ - Anode utilisation

Tc - Theoretical anode capacity A.y per anode from (3)

Available anode capacity $Ac = 0.0057 \times 0.8 \times 0.9$

$$Ac = 0.0041 \text{A.y or } 4.1 \text{ mA.y per anode} \qquad (4)$$

For this example, it can be seen that approximately 72% of the theoretical anode capacity is available for cathodic protection purposes, the remaining 28% is not considered in the design process and can be considered as a safety factor.

Stage 4 - Design life, total cathode current demand

The design life of a cathodic protection system is related to the total energy required to stop and prevent corrosion of the steel. The actual life of preventing concrete deterioration may be much longer than the operational life of the anodes and depends on the state of the steel following the application of cathodic protection and prevailing environmental conditions.

For most galvanic anode systems, a minimum anode design life of 10 years is required.

The method of current demand calculation can be approached in two ways, the first is

- assuming a constant current demand with time
- the alternative is based on the phased current demand which is reducing with time due to passivation effects of the applied cathodic protection.

Constant current demand

This design life is then used to calculate the total cathode demand for the 10 year period using the calculated cathode current demand shown in (2).

Cdt = Cd x dl

Cdt – total cathode current demand for life (A/m^2 concrete)

Cd – cathode current demand (Ay/m^2) from (2)

dl – Design life (y)

Total cathode current demand 0.00385Ay for 0.716m^2 steel for 10 years

Cdt = 0.00385Ay/m^2 concrete x 10 years

= 0.0385A per m^2 concrete for a 10 year life (5)

This current demand is considered to be overly conservative, requiring a constant current density of 3.85 mA/m^2 over the 10 year operational life.

Phased current demand

In practice, due to the effects of reducing chloride and increasing hydroxide ion concentration with time, as described in stage 2, a lower total current demand based on the phase current demand process may be considered for design purposes.

- Phase 1 - Initial high current density, required for stopping corrosion at maximum chloride levels (for 0.2-0.3Wt%Cl-, a design current density of 5.38 mA/m2 is required for 1 year).
- Phase 2 - Reduced current density required 75 % of original design current density, required for healing the passive film following reduction of chloride levels at the steel surface. (for 0.2-0.3Wt%Cl-, a design current density of 4.035 mA/m2 is required for 1 year).
- Phase 3 - Maintenance or cathodic prevention current density, following passive film stabilisation, required to prevent pit initiation and pit stabilisation (2 mA/m^2 for the remaining life, based on the maximum current density listed within ISO 12696 for cathodic prevention).

Using the approach detailed above, the individual current demand of each phase can now be calculated.

Cd1 phase 1 (2a) for 1 year = 0.00385Ay x 1 = 0.00385A

Cd2 phase 2 (2b) for 1 year = 0.00289Ay x 1 = 0.00289A

Cd3 phase 3 (2c) for 8 years = 0.00143Ay x 8 = 0.01146A

The total current demand for the phased approach is then determined by addition of the individual phased current demands as follows:

Cdtp = Cd1 + Cd2 + Cd3

Cdtp – total phased cathode current demand for life (A/m^2 concrete)

Cdtp = 0.00385A + 0.00289A + 0.01146A

Cdtp = 0.0182 A per m^2 concrete for a 10 year life (6)

Or a mean current density of 0.0182A/m^2/10 years = 0.00182A per m^2 concrete for a 1 year life as detailed in stage 13.

Stage 5 – Minimum number of anodes based on actual anode capacity

The minimum number of anodes required to provide protection to 1m^2 of concrete is then estimated using the total cathode current demand (5) or (6) and the available anode capacity (4) as follows:

Na = Cdt / Ac

Na = Number of anodes in 1m^2 concrete

Cdt – total cathode current demand for life (A/m^2 concrete)

Cdtp – total phased cathode current demand for life (A/m^2 concrete)

Ac - Available anode capacity (listed as A.y per anode, but only A used for quantity assessment for total current demand)

For a constant current demand as detailed in (5)

From (4) & (5) Na = 0.0385 A/m2 / 0.0041 A

Na = 9.4 anodes

Number of anodes required in 1m^2 concrete Na = 10 No (7)

For a phased current demand as detailed in (6)

From (4) & (6) Na = 0.0182 A/m2 / 0.0041 A

Na = 4.44 anodes

Number of anodes required in 1m^2 concrete Na = 5 No (8)

Stage 6 – Calculating anode resistance

The resistance of a point source anode, installed at depth below the concrete surface, can be determined using the following resistivity formula, sourced from ‘Handbook of Cathodic Protection’ Baeckmann, Schwenk, Prinz

$$\boxed{R=(P/2\pi L)\ LN\ (2L/D\ \sqrt{(4T+3L/4T+L)})}$$

R – Individual anode resistance (Ohm)

P - Concrete resistivity (Ohm.m)

L - Anode length (m)

D - Anode diameter (m)

T - Anode depth (m)

The following parameters have been selected for example purposes.

- Concrete resistivity - 200 Ohm.m
- Anode length – 0.1m (100mm)
- Anode dimeter – 0.025m (25mm)
- Depth below concrete surface – 0.05m (50mm)

Individual anode resistance $R = (200/(2 \times \pi \times 0.1)\ \mathrm{Ln}\ [(2 \times 0.1/ 0.025) \times \sqrt{\{(4 \times 0.05 + 3 \times 0.1)/(4 \times 0.05 + 0.1)\}}$

R = 743 Ohm per anode (9)

Anode are installed into a parallel arrangement, where the total resistance of the anode cluster can be determined using the following resistance formula for a parallel circuit.

$1/R_t = 1/R_1+ 1/R_2\ldots.$

Rt – Total anode cluster resistance (Ohm)

R – Individual anode resistance (Ohm)

For a constant current demand as detailed in (5) and a requirement of 10 anodes (7), the total anode resistance for this cluster of anodes can be determined from (9) as follows:

Rt = 1 / [(1/743) x 10]

Total anode cluster resistance Rt = 74.3 Ohms (10)

For a phased current demand as detailed in (6) and a requirement of 5 anodes (8), the total anode resistance for this cluster of anodes can be determined from (9) as follows:

Rt = 1 / [(1/743) x 5]

Total anode cluster resistance Rt = 148.6 Ohms (11)

Note at this stage the calculation does not consider any interference effects associated with anodes in close proximity to one another, which is expected to increase the total anode cluster resistance.

Stage 7 –Anode to cathode driving voltage

Galvanic anode systems rely entirely on the inherent potential or voltage (energy) difference between the anode and cathode to drive the cathodic protection current.

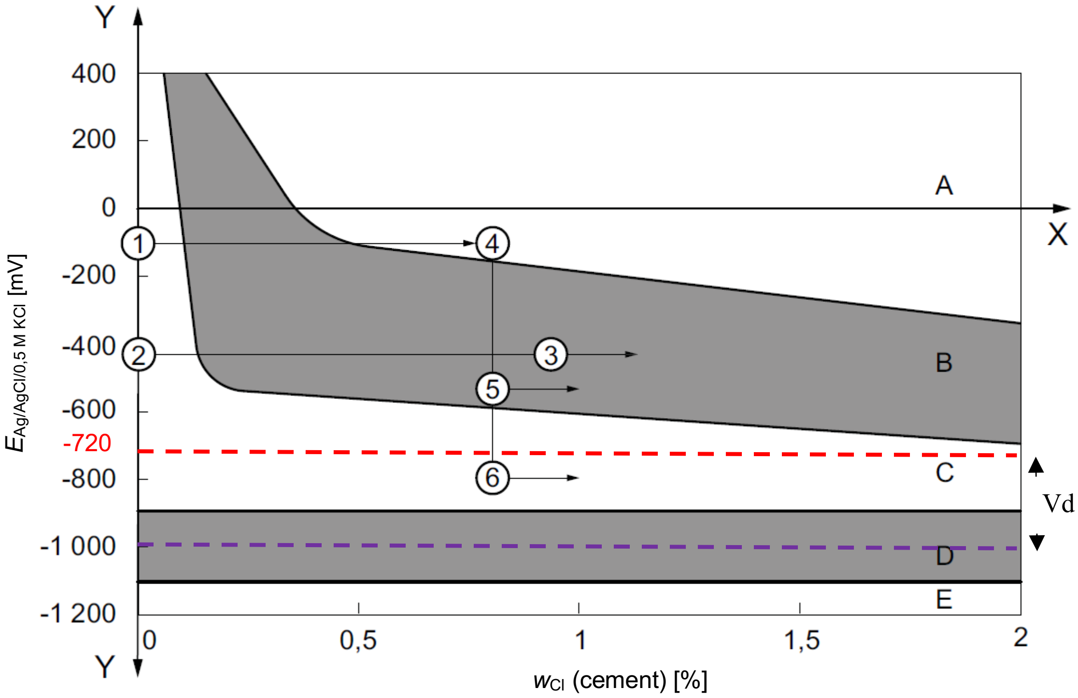
Anode open circuit potentials may vary slightly based on the anode material or the pH of the backfill surrounding the anode. A typical open circuit potential for zinc roll anodes embedded in concrete, is approximately -1.000 Volt Ag/AgCl 0.5M KCl.

The potential of steel in concrete, which is subjected to corrosion and cathodic protection can vary significantly based on a number of factors, including, oxygen concentration, chloride concentration, concrete resistivity, concrete relative humidity, state of steel surfaces (passive or active), cement type, hydroxide to chloride ratio etc.

The minimum steel potential which is suitable to use for calculating the anode to cathode driving voltage needs to consider both the chloride concentration and the risk of corrosion pit initiation and pit propagation.

BS EN ISO 12696 lists an instant off potential of /or more negative than -0.72 Volt Ag/AgCl 0.5M KCl as a suitable criterion which is applicable for stopping corrosion within active corrosion pits.

The following figure identifies the risk of corrosion against chloride concentration and potential, superimposed on the graph is the -0.72 V protection criteria and the -1.00 V anode open circuit potential.



Pitting potential vs. chloride content in percentage by mass of cement - ISO 12696 Figure A.3

Key

Protection criteria – – –
Anode open circuit potential – – – ·
Area A: Pitting initiates and propagates
Area B: Pitting does not initiate but propagates
Area C: Pitting does not initiate and propagates
Area D: Hydrogen embrittlement risk to high-strength steels
Area E: Reduction of steel/concrete bond
Cathodic prevention (1→2→3)
Cathodic protection restoring passivity (1→4→6)
Cathodic protection reducing corrosion rate (1→4→5).

From the above graph it can be seen that a steel potential of -0.72V Ag/AgCl 0.5M KCl will place the steel in Area C, where pitting cannot initiate and where existing pits cannot propagate even for levels of chloride in excess of 2 Wt% Cl^- to cement.

Selecting -0.72 Volt Ag/AgCl 0.5M KCl as the cathode protection potential enables the calculation of the initial anode to cathode driving voltage for worse case conditions (i.e when the highest current density is required to passivate active pits).

Note- the application of cathodic protection current to steel surfaces in concrete will lead to changes in the state of the steel, increasing the level of passivity, leading to a more positive rest potential. This effect is expected to increase the anode to cathode driving voltage with time, for surfaces with access to unlimited oxygen due to steel passivation effects associated with cathodic protection.

This phenomenon is only applicable for surfaces with access to free oxygen and this effect may not be observed in oxygen depleted (under coatings) or saturated conditions where the rest potential may become more negative with time.

The driving voltage or potential difference can now be calculated using the following information.

- Instant off cathodic protection criteria clause 8.6 a within BS EN ISO 12696 is listed as an instant off potential of or more negative than -0.72 Volt Ag/AgCl 0.5M KCl.
- Zinc anode open circuit potential of -1.00 Volts Ag/AgCl 0.5M KCl

Vd = Va - Vpc

Vd – available driving voltage (V)

Va – anode open circuit driving voltage (V)

Vpc – cathode protection criteria voltage (V)

Available driving voltage Vd = -1.00 - (-0.72)

$$Vd = 0.28V \tag{12}$$

An initial worst case, steady state driving voltage of 0.28 Volt is available to drive current from the galvanic anode to the embedded reinforcement.

It should be noted that the initial driving voltage observed following anode to cathode connection is much greater than the steady state driving voltage used for anode life and spacing calculations. This initial driving voltage, results from non- equilibrium conditions where there is an unrestricted supply of oxygen and where the mixed potential has yet to be achieved.

Under these initial non-equilibrium conditions, a much higher current can be delivered to the steel, than calculated within the design, which may contribute to more rapid pit passivation with time.

Stage 8 –Anode to cathode current from the anode resistance and driving voltage

The anode to cathode current can now be calculated using Ohms law and the following:

- driving voltage Vd (12)
- individual anode resistance R (9)

Using ohms law,

I = Vd/R

I – Available current (A)

Vd - Driving voltage (V)

R – Individual anode resistance (Ohm)

Individual anode current

I = Vd (12) / R (9)

I = 0.28/743

Available Current (A) I = 0.000377A (0.377mA) (13)

This is the expected available current a single anode installed in to 200 ohm concrete can provide, without considering the impact of parallel anodes or associated anode interference effects.

Stage 9 – current demand vs anode current supply check

Based on single roll anode installed vertically within a concrete resistivity of 200 ohm.m, each anode can pass a maximum of 0.000377A (0.377mA) per anode at a driving voltage of 0.28V.

This current can now be compared against the cathode current demand required per m^2 concrete.

- Current density required under constant demand – 0.00385A per m2 concrete from (2)
- Worst case current density under phased demand - 0.00385A per m2 concrete from (2a)

The minimum number of anodes can then be determined for the cathode current demand calculated in (2 or 2a) as follows

Nr = Cd/Ia

Nr- number of anodes required to meet cathode current density

Cd –cathode current demand (A/m^2 concrete)

Ia - Individual anode current (A)

Nr = 0.00385A / 0.000377 A

= 10.2 anodes

Nr = 11 anodes required to meet Cd (14)

A current check using the stage 6 & 7 formula is now undertaken to validate the anode selection process.

Where Rt = 1 / [(1/743) x 11]

Rt = 67.55 Ohm

I = 0.28/67.55

Total anode current provided I = 0.0041 A (15)

Cathodic current demand from (2, 2a) Cd = 0.00385A per m^2 concrete

This assessment has identified that the supplied combined anode current is more than the cathode current demand calculated in (2) 0.00385A per m2 concrete, as a result the current provided is sufficient to meet the minimum cathode current demand for cathodic protection under both constant current density conditions and for the worst case phased current density conditions.

Stage 10 – Anode interference factor & effect on anode quantity

Anodes installed in close proximity to one another, have a direct impact on the individual anode resistance and subsequent anode output. This results in a lower overall anode output for multiple, closely spaced anodes compared to that calculated for a single anode in similar conditions.

It is possible to determination the impact of this interference on the anode resistance, using the following formula sourced from 'Handbook of Cathodic Protection' Baeckmann, Schwenk, Prinz.

$$Rn = [R/n]\ F$$

Rn- Total resistance of n anodes

R – individual anode resistance from (9)

N – number of anodes from (14)

F – interference factor is between 1.2 & 1.4 (1.4 a worst case condition has been selected for this assessment)

Rf – anode resistance including interference factor

Total resistance of n anodes Rn = [743/11] x1.4

Rn = 94.56 ohm (16)

Rn is now added to the original anode resistance to obtain the new resistance, accounting for anode to anode interference effects.

Rf = R + Rn

Rf = 743 + 94.56

Rf =837.56 ohm (17)

A current check using the stage 6 & 8 formula is now undertaken to validate the anode selection process.

Where Rt = 1 / [(1/837.56) x 11]

Rt = 76.14 Ohm

I = 0.28/76.14

Total anode current provided I = 0.00367 A (18)

Cathode current demand from (2) Cd = 0.00385A per m^2 concrete

This shows that due to the anode interference effect on the anodes, 11 No anodes are not sufficient to meet the cathode current demand and as such 12 anodes will be required.

Using the interference formula and process above for 12 anodes Rn = 86.68 and Rf = 829.68 Ohm

A current check using the stage 6 & 8 formula is now undertaken to validate the anode selection process.

Where Rt = 1 / [(1/829.68) x 12]

Rt = 69.14 Ohm

I = 0.28/69.14

Total anode current provided I = 0.00405 A (19)

Cathodic current demand from (2) Cd = 0.00385A per m^2 concrete, is less than anode current provided = **pass**.

Stage 11 - Estimating anode spacing

Based the required number of anodes, 12 No within a 1m^2 of concrete, it is possible to identify the anode to anode spacing using the following formula:

As = √[1/Nr]

As – anode spacing (m)

Nr - number of anodes required

Anode spacing = √[1/ number of anodes required]

As = √[1/12]

As = 0.288m (21)

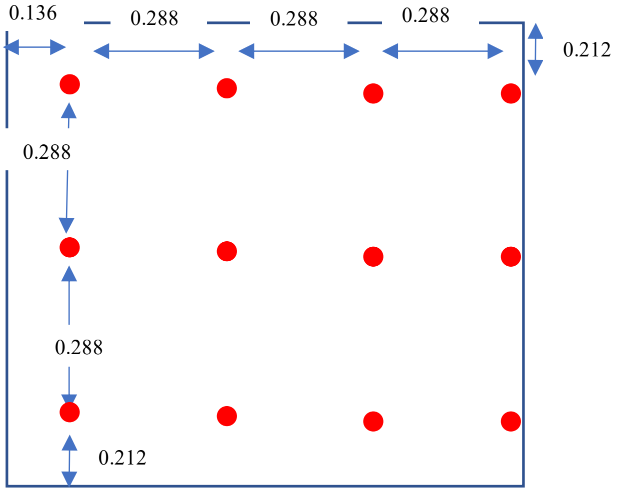


Figure 1 showing a typical anode spacing within 1 m2 concrete starting from the edge of a structure

Stage 12 - Expected voltage rise at ½ anode spacing

The next stage of the assessment is to determine the expected voltage shift at ½ of the anode spacing, (furthest point) as a result of the anode current, depth and concrete resistivity.

The voltage rise, at ½ anode spacing of a point source anode installed at depth below the concrete surface can be determined using the following voltage gradient formula sourced from ‘Handbook of Cathodic Protection’ Baeckmann, Schwenk, Prinz.

$$Ur=(IP/2\pi L)\ LN\ [(T+L+\surd\{r^2+(T+L)^2\})/(T+\surd\{r^2+T^2\})]$$

Ur – change in voltage at distance r from the anode (V)

P - Concrete resistivity (Ohm.m)

I -Current -per anode (A)

L - Anode length (m)

T - Anode depth (m)

r – distance from anode (half anode spacing) (m)

The following parameters have been selected based on the previous stages:

- Concrete resistivity - 200 Ohm.m
- Current per anode - Ia = 0.000338A per anode (using interference factor and current in (19)/12 anodes)
- Anode length – 0.1m (100mm)
- Depth below concrete surface – 0.05m (50mm)
- Distance from anode - ½ anode spacing - 0.144m (144mm)

$$Ur = [(200 \times 0.000338) / (2 \times \pi \times 0.1)]\ Ln\ [(0.05+0.1 + \surd\{0.144^2 +(0.05 +0.1)^2\}) / (0.05+\surd\{0.144^2 +0.05^2\})]$$

$$Ur = 0.0613V\ (61mV) \qquad (22)$$

The above voltage shift is for a single anode, and given that multiple anodes are installed within a 1 m^2 of concrete, a combined voltage shift from two coinciding voltage cones is expected to be at least 122mV and a combined voltage shift from 4 coinciding voltage cones is expected to be >122mV.

Stage 13 - Expected anode life based on anode selection

The final stage of assessment is to determine the expected life from the anodes selected, based on anode mass, quantity, anode efficiency and utilisation as follows:

Ac - Actual anode capacity = 0.0041A.y or 4.1mA.y per anode from (4)

Nr -Number of anode = 12 No from (19)

Cd Cathode current demand for 1 year under constant current density = 0.00385A/m^2 concrete from (2)

For the phased current density approach, a mean current density can be determined as follows:

Cdpm = Cdtp / dl

Cdtp - Total phased current demand for 10 years = 0.0182 A/m^2 concrete from (6)

dl - Design life 10 years from stage 4

Cdpm - Mean cathode current demand for 1 year under phased current density conditions (A/m^2)

Cdpm = Cdtp / dl

= 0.0182A/m^2 /10 y

Cdpm = 0.00182 A/m^2 concrete

The total available anode capacity is determined as follows:

Tac = Nr x Ac

Tac - total available anode capacity A.y

Na = Number of anodes in 1m^2 concrete

= 12 x 0.0041A.y

= 0.0492A.y (23)

The theoretical anode life is then determined for constant current conditions as follows

Talc - theoretical anode life for constant current demand

Talc = Tac / Cd

= 0.0492A.y / 0.00385A/m2

= 12.78 years (24)

Talp - theoretical anode life for mean phased current demand

Talp = Tac / Cd

= 0.0492A.y / 0.00182A/m2

= 27 years (25)

Discussion and conclusion

From the above assessment, it can be concluded that for a structure with:

- a concrete resistivity of 200 Ohm.m
- contain a single reinforcement mat consisting of T32 bars at 0.25 centres and T25 bar at 0.25m centres
- with a chloride to cement content of 0.2-0.3wt% Cl-
- the conditions detailed in scenario 3 and a design current density of 5.38mA/m^2

That a minimum of 12 No anodes (0.1m long x 0.025m dimeter) are required at a spacing of 0.288m centres.

This approach has selected an anode to cathode driving voltage of 0.28V based on a final protection potential of -0.72V Ag/AgCl 0.5M KCl, which is required to stop and prevent pitting corrosion within active pits.

This approach provides a predicted voltage rise in excess of 100mV at the furthest point for the anodes, which may help to meet the required 100mV criteria listed within the ISO 12696 standard.

Under constant cathode current density conditions, the installed anodes are expected to last for 12.78 years

Under mean phased, cathode current density conditions, the installed anodes are expected to last for 27 years

Design current density method

The design current density method (continuous or phased) used for determining the total current demand, does not affect the overall number of anodes needed, which appears to be controlled by the anode resistance and anode interference effects. This is due to the requirement to deliver the initial maximum design current density during the initial phase of protection for both continuous and phased current density protection approaches.

The design current density method (continuous or phased) does however have a significant impact on the required anode capacity, meaning that where a phased current density approach is adopted, the amount of anode mass required to meet the anode design life can be significantly reduced compared with a continuous current density approach.

Under continuous current density conditions, a minimum of 9.4 anodes is required, equivalent to an overall anode mass of 0.573kg/ m^2 concrete, for a 10 year life.

Under phased current density conditions, a minimum of 4.44 anodes is required, equivalent to an overall anode mass of 0.270kg/ m^2 concrete, for a 10 year life.

From an application perspective the phase current density approach is similar to what has been used and demonstrated to be successful on marine structure for many years. These structures develop resistive calcareous layers on metal surfaces, as a result of the application of cathodic protection, which results in a reduction of oxygen availability and generates and maintains hydroxide at the steel surfaces, which leads to an overall reduction of current demand with time.

Impact of anode shape on life

As the anodes corrode the surface areas reduce, which leads to an increase in the overall anode resistance and a reduction of anode current output. In opposition to this affect is the increasing of the driving voltage which is expected with time (for structures with unrestricted oxygen access), due to the positive shift of the cathode open circuit potential resulting from re- passivation of the steel surfaces and the reduction in current density required to maintain passivity.