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Performance assessment of cathodically protected reinforced concrete structure based on alternative performance criterion: a case study

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Abstract

Performance of cathodic protection system in reinforced concrete structures is generally evaluated using 100 mV decay criterion. This approach is widely used, however has its own limitations. Recently, a new approach by determining the actual corrosion rate using the Butler Volmer equation has become an 'alternative' criterion for assessing the performance of cathodic protection system. This paper deals with critical examination and practical application of Butler-Volmer Equation to judge the effectiveness of cathodic protection system. Sensitivity analysis of various input parameters through numerical modelling by parametric studies showed significant dependence of corrosion rate on cathodic Tafel slope. One-year field data from a cathodic protection monitoring site in UK was collected and variability in the two approaches was assessed.

Keywords: Cathodic Protection, Reinforced Concrete, Butler-Volmer equation, Corrosion rate, Protection Criteria, Numerical Modelling

1. Introduction

Reinforcement corrosion is insidious in nature and its initiation and early stages of propagation cannot be detected visually. Yet early detection of corrosion in reinforced concrete (RC) structures as generally advocated can provide the opportunity of early interception in its progression, thereby ensuring the safety of the structure. If corrosion processes are left unchecked until cracking or spalling occurs, then the costs of repair are significantly higher because almost all of the concrete cover and heavily corroded section(s) of the reinforcement must be removed and replaced, especially where pitting occurs. Because of the multi-billion pounds direct and indirect cost of deterioration of reinforced concrete structures due to corrosion (particularly chloride-induced corrosion), a number of different corrosion monitoring methods and techniques have been developed [1]. This is not only to identify and quantify the extent and rate of deterioration but also to assess and evaluate the performance and effectiveness of the corrosion mitigation and protection methods.

Cathodic protection (CP), an electrochemical technique, has long track records to stop or mitigate corrosion of steel in various environments, including the steel reinforcement in chloride contaminated concrete [2–5]. Cathodic protection involves applying a negative potential to the metal to be protected via an external electric circuit (Impressed Current Cathodic Protection, ICCP) or by attaching a sacrificial anode (Sacrificial Cathodic Protection, SACP) which corrodes more readily to the metal (e.g. steel reinforcement) donating its electrons to the metal requiring protection [6]. This causes the potential to become more negative and tends to take the metal into the immunity region on the Pourbaix diagram [7, 8].

All aspects of the cathodic protection system design, installation and performance assessment are undertaken to comply with the national and international standards. The regular assessment of the performance and effectiveness of installed CP systems, either ICCP or SACP, is an essential requirement to ensure that the on-going corrosion is mitigated or halted. The international standard, BS EN ISO 12696:2016 *Cathodic Protection of Steel in Concrete* provides a set of CP performance criteria. CP for any structure shall meet any one of the following criterion [9]:

- An ''instantaneous OFF'' potential more negative than -720 mV with respect to Ag/AgCl/0.5M KCl; or
- A 'potential decay' over a maximum of 24 hours of at least 100 mV from ''instantaneous OFF'' value; or
- A 'potential decay' over an extended period (typically 24 hours or longer) of at least 150 mV from ''instantaneous OFF'' value, subject to continuing decay and the use of reference electrodes (not potential decay probes) for the measurement extended beyond 24 hours.

The above three criteria are based on the measurement of a thermodynamic parameter, i.e. electrode potentials, and are widely used for both ICCP and SACP system. However, accomplishing immunity and thermodynamic reversibility is difficult by some structures exposed to variable environmental conditions [10]. Thus, to achieve controlled corrosion, the corrosion process kinetics (i.e. corrosion rate) is reduced sufficiently that corrosion appears to be stopped. This is the mechanism by which 100 mV decay criterion controls corrosion [10]. However, this method was developed using laboratory experimentation and is not applicable for mixed metal structures as galvanic coupling of the mixed metals may create and lead to an inaccurate apparent level of protection [10, 11]. Moreover, for structures containing sulphate reducing bacteria and exposed to elevated temperature the results obtained are unreliable [12, 13]. Furthermore, researchers still questions the theoretical background of this criterion.

In addition to these criteria, the latest Standard BS EN ISO 12696 [9] has criterion just for the performance assessment of sacrificial anodes, based on kinetics parameters such as corrosion rate measurements following the application of cathodic protection. With regard to corrosion rate measurement and calculations, the standard recommended using the Butler-Volmer equation without further elaboration, except referring to a technical publication for the detailed procedures to site measurements and the corrosion rate calculation.

Non-compliance of the performance criteria, particularly the '100 mV decay', may not be achieved for structures with SACP system but this does not necessarily indicate that the structure is actively corroding; since the application of cathodic protection has an important beneficial effect to alter the surface chemistry of the corroding steel reinforcement. This is due to the generation of hydroxyl ions (OH^-) resulting from the cathodic reduction of oxygen (i.e. $O_2 + 2H_2O + 4e^- \rightarrow 4\ OH^-$); and subsequent formation of oxide layers on the steel surface causes the reinforcement to become passive. This, in turn, reduces the corrosion rates. It is, therefore, logical to have a criterion based on the measurement of corrosion rate before and after the application of cathodic protection in order to evaluate the overall performance of a CP system and the effectiveness of the anode system used.

This paper critically examines the improved method for monitoring the corrosion rate through the Butler Volmer equation using the polarization data, which forms the basis for monitoring the efficacy of CP structure to be used by consulting engineers. The sensitivity of input parameters of Butler Volmer equation has been analysed using numerical modelling by use of FEM software Comsol Multiphysics 5.3a. The outcome of this study is also a significant improvement to national standard for corrosion assessment of RC structures. Finally, a pilot application of the proposed method was used to evaluate one-year monitoring data collected from a cathodically protected highway structure i.e. twenty 16m-span viaduct in Peterborough, Cambridgeshire, UK, to help a client with corrosion management of their assets.

2. New Approach for CP Performance Assessment

A new approach for monitoring CP performance in reinforced concrete structure is dependent on improved Butler Volmer (B-V) equation, as given in equation 1. The detailed analysis of the method is given in the author's previous work [14].

$$i_{\mathrm{app}} = i_{\mathrm{corr}}\{exp\left(\frac{2.3\Delta E}{\beta_{\mathrm{c}}}\right) - exp\left(\frac{-2.3\Delta E}{\beta_{\mathrm{a}}}\right)\} \qquad \text{(Equation 1)}$$

Where i_{app} is the applied current density, i_{corr} is the corrosion rate, ΔE is the potential shift and β_a and β_c are constants.

The method uses polarization results from CP monitoring data, in which the steel/concrete/electrode potential shift, and applied current density are the main parameters. The Tafel slopes are obtained by plotting the change in steel/concrete/electrode potential against the logarithm of the applied current after each polarization. The slope of the curve will give an indication of the Tafel slopes.

The obtained corrosion rates can then be related to the condition of the rebar suggested by various researchers based on the combination of laboratory, and field studies (Table 1) [15–17].

Table 1. Corrosion current vs. condition of the rebar (Report 2004)

Corrosion current (I_{corr}), µA/cm^2	Corrosion current (I_{corr}), mA/m^2	Condition of the rebar/ corrosion rate
< 0.1	<1	Passive
0.1 – 0.5	1 – 5	Low to moderate corrosion
0.5 – 1.0	6 – 10	Moderate to high corrosion
>1.0	>10	High corrosion

In line with the above findings, BS EN ISO 12696 recommends that the corrosion rate of 2 mA/m^2, preferably less than 1 mA/m^2 is interpreted as the state of passivity [9]. Implicit in this analysis is that if the calculated corrosion rate is 2 mA/m^2 or less, then the installed CP anodes are considered to be providing sufficient protection current.

3. Numerical Model for Sensitivity Analysis of input parameters of B-V equation

The sensitivity of input parameters of the Butler Volmer equation has been analysed using numerical modelling by the use of FEM software Comsol Multiphysics 5.3a.

The potential and current distribution inside the concrete follows Laplace equation (2) and Ohm's law (3), assuming electrolyte is homogeneous [18]:

$$\nabla^2 E = 0 \quad \text{(Equation 2)}$$

$$I_{xj} = \sigma \nabla E \quad \text{(Equation 3)}$$

The total current density for any part of the electrolyte surface can be calculated using Ohm's law as:

$$I_s = \sigma \frac{\partial E}{\partial n} \quad \text{(Equation 4)}$$

Where ∇ is Nabla operator, ∇^2 is Laplace operator, I_{xj} is current flowing in direction xj in Amperes, E is the difference between external electric potential of steel bar (considered as zero as a reference) and electrolyte potential in Volts, I_s is total current density in Ampers per meter square and σ is the electrolyte conductivity of the concrete in Siemens per meter.

Two different electrode reactions were considered on the steel rebar boundary: iron oxidation and oxygen reduction:

$$Fe \rightarrow Fe^{2+} + 2e^- \quad \text{(Equation 5)}$$

$$O_2 + H_2O + 4e^- \rightarrow 4OH^- \quad \text{(Equation 6)}$$

Reaction kinetics of these reactions are modelled at the steel-concrete interface using the Tafel expressions obtained from polarization curves and fitting it into Butler Volmer Equation:

$$\mathrm{i} = i_{Fe}^{o}\left[\exp\frac{2.3(\mathrm{E}-\mathrm{E}_{Fe}^{o})}{\beta_a}\right] - \frac{i_{O2}^{o}\left[\exp\frac{2.3(\mathrm{E}_{O2}^{o}-E)}{\beta_c}\right]}{1+\frac{i_{O2}^{o}}{i_L}\left[\exp\frac{2.3(\mathrm{E}_{O2}^{o}-E)}{\beta_c}\right]} \quad \text{(Equation 7)}$$

Where i is current density on steel surface, i^o is exchange current density; β_a and β_c are anodic and cathodic Tafel slope, i_L is the limiting current density and E^o is equilibrium potential

At all isolating surfaces, vector normal to potential gradient is considered zero:

$$\frac{\partial E}{\partial n} = 0 \quad \text{(Equation 8)}$$

For this study, the application of CP to steel bars in concrete was modelled as a two-dimensional cross-section. A slab of dimension 200×70 mm with two steel bars of 10 mm diameter with 150 mm spacing was modelled. The concrete cover was set to 25 mm. The input parameters are reported in Table 2 and fitted into equation 7. For the CP anode, a surface applied arrangement has been set and constant current density was applied from top surface using electrolyte current density node as an inward electrolyte current density. To simplify the analysis, anodic resistivity and polarization behaviour have been ignored. Moreover, all the reinforcement bars were considered to be in the active state.

Table 2. Input parameters for active rebar

Parameters	**Values**
Anodic Tafel Slope (β_a)	0.41[V/dec]
Cathodic Tafel Slope (β_c)	-0.18[V/dec]
Anodic Equilibrium Potential Vs Ag/AgCl (E^o_{Fe})	-0.76[V]
Cathodic Equilibrium Potential Vs Ag/AgCl (E^o_{O2})	0.189[V]
Anodic Exchange Current Density (i^o_{Fe})	7.1e-5[A/m^2]
Cathodic Exchange Current Density (i^o_{O2})	7.7e-7[A/m^2]
Limiting Current Density (i_L)	100[mA/m^2]

The top surface of the concrete was considered as an anode and an average constant current density of 5 mA/m^2 was applied from anode to steel (Fig. 1). Concrete resistivity was considered as 100 Ωm to simulate a typical site condition.

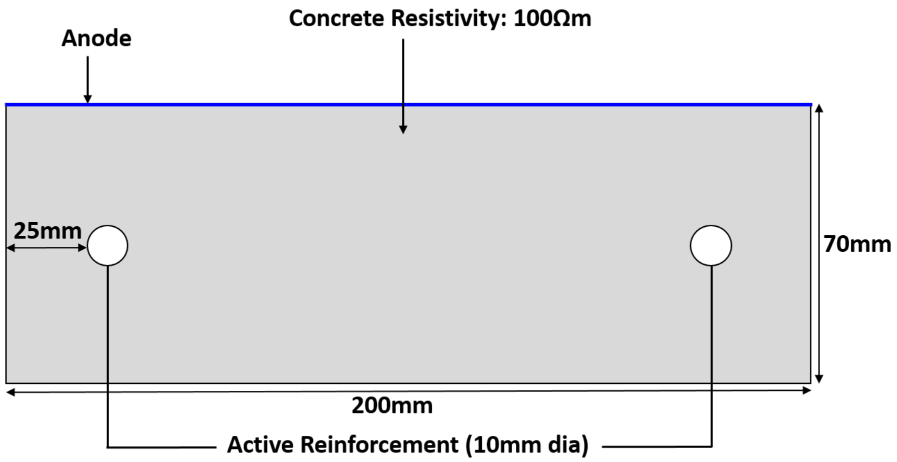


Fig. 1 The geometry of numerical model

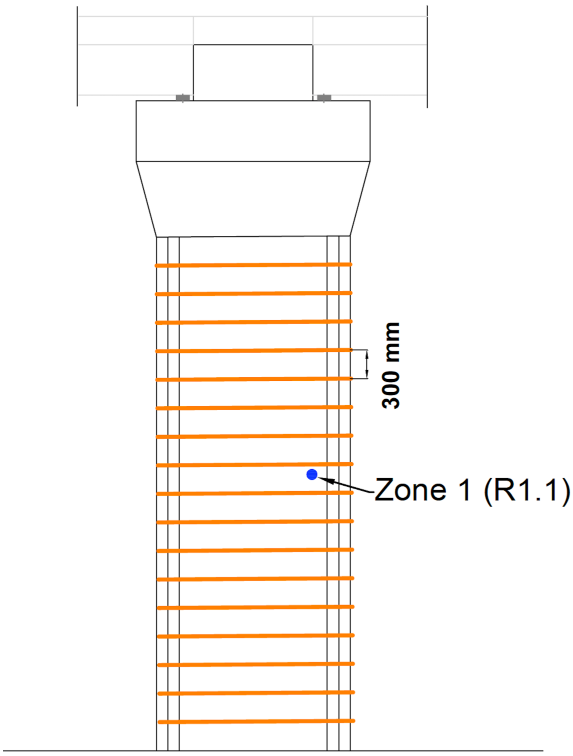
A parametric study has been carried out to assess the influence of input parameters of the B-V equation on the corrosion rate. Influence of three parameters: anodic (β_a), cathodic (β_c) Tafel slope and applied current density (i_{app}) were studied. Anodic and cathodic Tafel slopes have been varied from 30 mV/decade to 300 mV/decade and applied current density from 5 to 20 mA/m^2.

4. Brief Description of the Case Study: Structure and Anode Systems

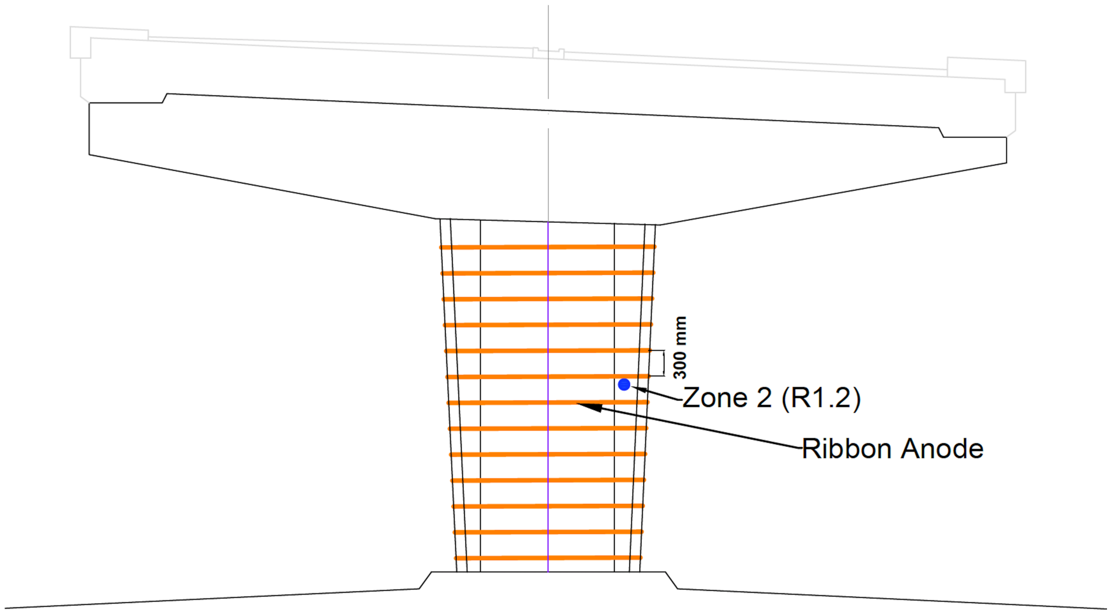
The proposed and improved method of CP evaluation was used to assess the performance of the twenty 16-span viaduct in Peterborough. The structure comprises 6 leaf piers and 14 T shape piers. Cathodic protection was applied to the structure in 2008 as part a major refurbishment scheme to prevent RC elements from further deterioration and reinforcement corrosion. For the present analysis, three piers were selected.

4.1 The Anode System

Three types of anodes were used for the installation of CP to the piers i.e. (a) De Nora LIDA 19mm diameter MMO/Ti based discrete anodes, (b) Elgard 150 expanded mesh anodes, and (c) Elgard 100 ribbon mesh anode. Pier 1 and 2 have similar geometry and are protected by installing rows of ribbon anodes on all four sides of a column at a typical spacing of 300mm (Fig. 2 (a) and (b)). The bearing shelf is protected by discrete anodes with ribbon anodes on soffit and sides (Fig. 2 (c)). Each pier is divided into a number of zones as shown in Fig. 2. For present analysis, four ribbon anode zones (two from column and two from crossbeam) and one discrete anode zone were selected from piers 1 and 2. Data were collected remotely using dedicated software and downloaded to an off-site computer in an Excel file format.



(a)



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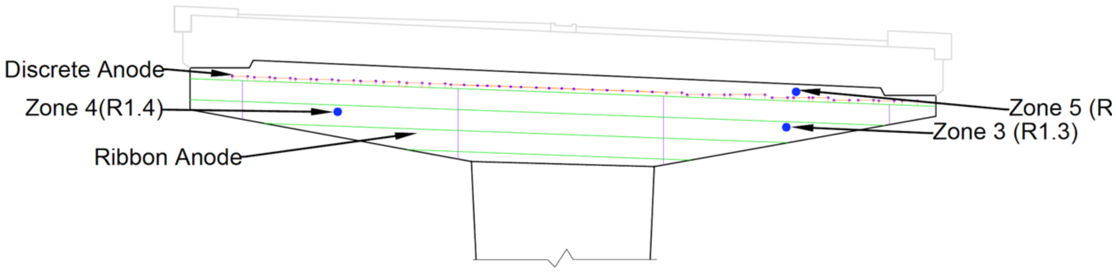

(c)

Fig. 2 Pier 1 showing anode placement (a) North Elevation Column: Zone 1 (North and South combine), (b) West Elevation Column: Zone 2 (West and East combine), (c) Crossbeam: Zone 3 (West), Zone 4 (East), Zone 5 (West and East combined)

Pier 3 is a leaf pier and has a discrete anode zone at the top and mesh anode zone on the side (Fig. 3). For analysis, one discrete anode zone and one mesh anode zone were selected. Details of all the CP zones and anode system are given in Table 3.

Table 3. Details of the selected elements and anode zones

Element	Zone	Reference Electrode ID	Anode system
Pier 1	1	R1.1	Ribbon mesh anode
	2	R1.2	Ribbon mesh anode
	3	R1.3	Ribbon mesh anode
	4	R1.4	Ribbon mesh anode
	5	R1.5	Discrete anode
Pier 2	6	R2.1	Ribbon mesh anode
	7	R2.2	Ribbon mesh anode
	8	R2.3	Ribbon mesh anode
	9	R2.4	Ribbon mesh anode
	10	R2.5	Discrete anode
Pier 3	11	R3.1	Expanded Mesh anode
	12	R3.2	Discrete anode

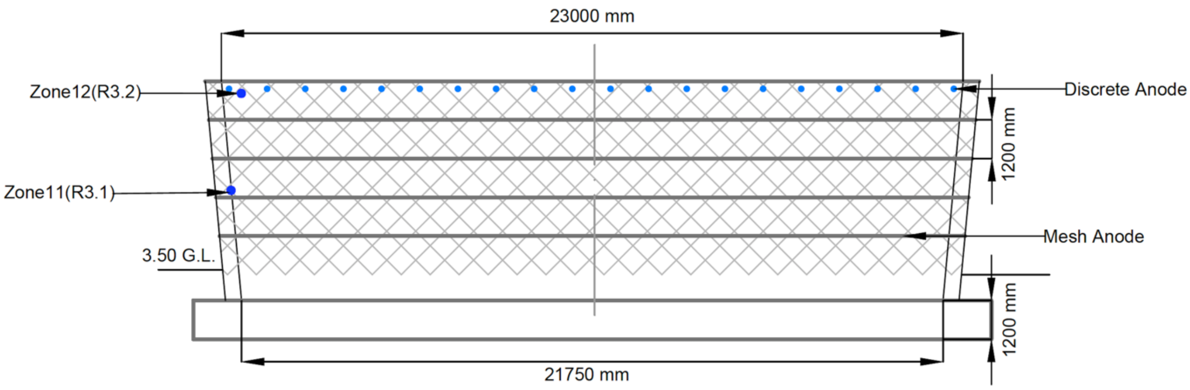

Fig. 3 Pier 3 showing anode arrangement: Zones 11 and 12 (West and east side combined)

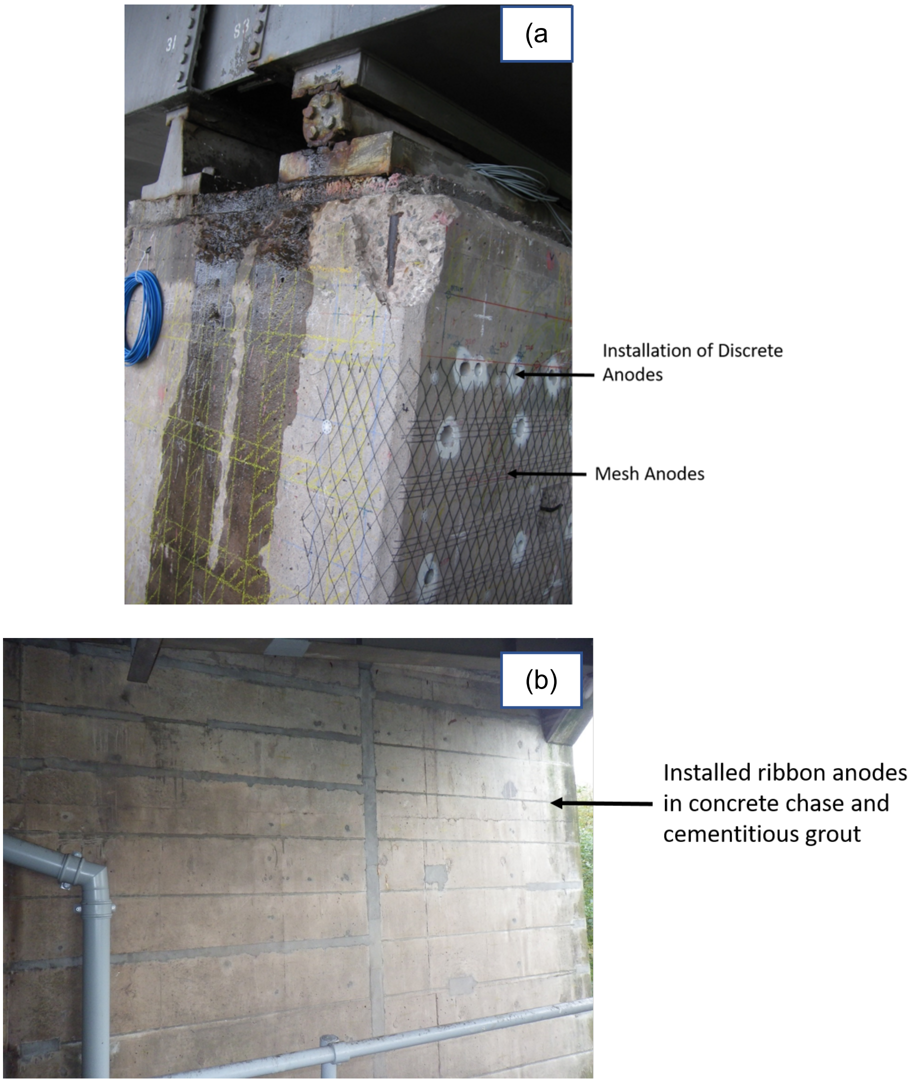

Fig. 4 Site images showing anode installation (a) Pier 3, (b) Pier 1 and 2

The site images of the installed and/or during the installation of various anode systems are shown in Fig. 4.

5. Analysis and Discussion

5.1 Sensitivity Analysis

The numerical results of the effect of different applied current densities (i_{app}) on corrosion rate are compared in Fig. 5. It can be shown that an increase in the current density results in a decrease in the corrosion rate. An applied current density of 5-20 mA/m^2, which is normally a lower and upper range of CP design current density, reduces corrosion rate by 63% from 0.17 mA/m^2 to 0.06 mA/m^2. The corrosion rate observed was low, considering the low initial corrosion rate of the rebar and also anode resistivity being ignored.

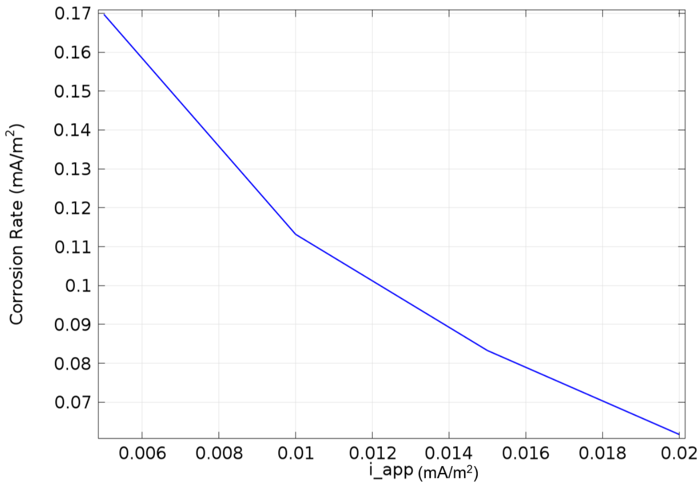

Fig. 5 Effect of applied current density on corrosion rate

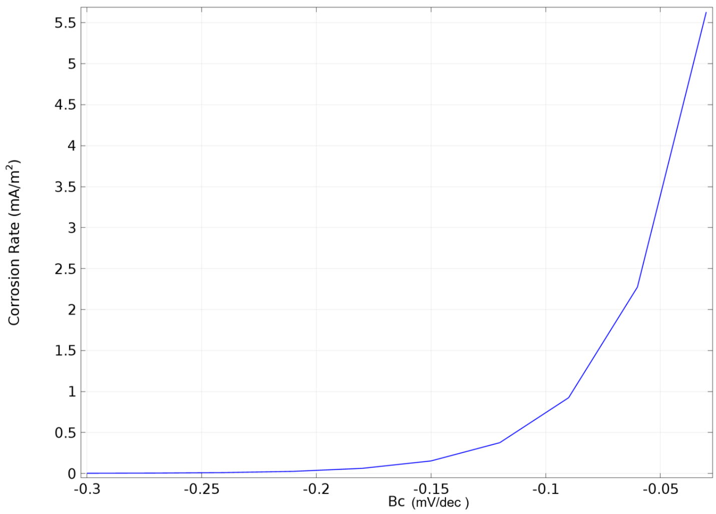

Fig. 6 Effect of cathodic Tafel slope on corrosion rate

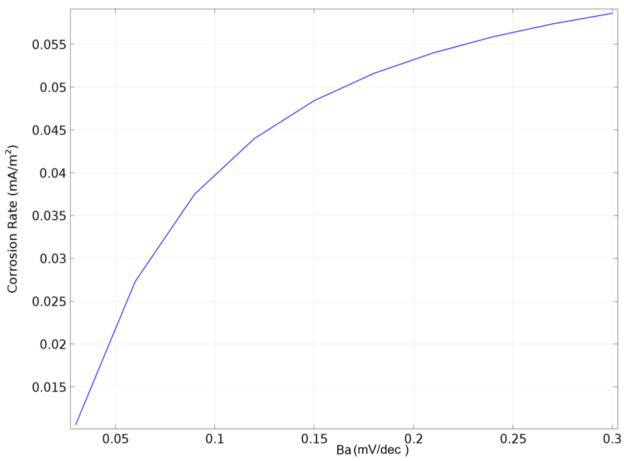

Fig. 7 Effect of anodic Tafel slope on corrosion rate

Fig. 6 and Fig. 7 shows the effect of variable cathodic and anodic slopes on corrosion rate estimation, respectively. It can be clearly observed that corrosion rate is mainly influenced by the cathodic Tafel slope (β_c) compared to the anodic Tafel slope (β_a). An increase of cathodic Tafel slope from 30 mV/dec to 300 mV/dec decreases corrosion rate from 5.6 mA/m^2 to 1.6 μA/m^2, thereby moving steel from moderate corrosion state to passive corrosion state as per Table 1. This indicates the sensitivity of the parameters. Conversely, the increase of anodic Tafel slope from 30 mV/dec to 300 mV/dec increased corrosion rate slightly from 0.01 mA/m^2 to 0.06 mA/m^2. Hence, corrosion rate estimation is more sensitive to β_c value compared to β_a. This confirms that considering a constant value for β_c for on-site corrosion rate measurement using linear polarization resistance method may result in significantly inaccurate measurement of the corrosion rate.

5.2 Performance assessment of CP at viaduct structure

5.2.1 CP monitoring using standard 100 mV decay criterion

Individual CP Zones were energised at an initial 25% of their design current density of 15mA/m^2 and then adjusted over time. The polarization behaviour of the anode zones were observed and analysed after a period of 1 month and 1 year by automatic pre-programmed switching off the power supply and monitoring steel/concrete 24 hours potential decay. All decay values were measured from instant off potentials with respect to silver/silver chloride reference electrodes. The results are shown in Table 4. All zones showed at least 100 mV decay after both 1 month and 1 year of polarization, thus satisfies the BS EN 12696: 2016 criterion [9]. However, this method only satisfied the standard requirement for performance of the CP technique and does not provide any information on corrosion rate of steel bars with which the remaining service life of the structure can be estimated.

Table 4. Polarization results for various zones after 1 month and 1 year

Zone	Reference Electrode	Potential shift (mV):1 month	Potential shift (mV):1 year	24 h decay (mV): 1 month	24 h decay (mV): 1 year
1	R1.1	-145	-128	160	143
2	R1.2	-166	-166	198	196
3	R1.3	-319	-290	301	262
4	R1.4	-200	-178	254	234
5	R1.5	-214	-155	235	188
6	R2.1	-155	-179	159	161
7	R2.2	-325	-300	215	280
8	R2.3	-265	-171	282	235
9	R2.4	-374	-333	274	242
10	R2.5	-293	-242	268	241
11	R3.1	-217	-224	149	156
12	R3.2	-186	-163	192	180

5.2.2 Corrosion rate determination from the proposed monitoring method

The cathodic Tafel slope (β_c) is obtained by plotting the change in steel/concrete/electrode potential against the logarithm of the applied current density, as shown in Fig. 8. It can be seen that β_c changes for different zones and is not constant (120 mV/dec) as considered in measuring corrosion rate using Linear Polarization Resistance (LPR) technique on site. Anodic Tafel slope (β_a) has minimal effect on the corrosion rate prediction as seen from numerical modelling and thus taken as a constant of 120 mV/dec, which is also used for LPR corrosion monitoring.

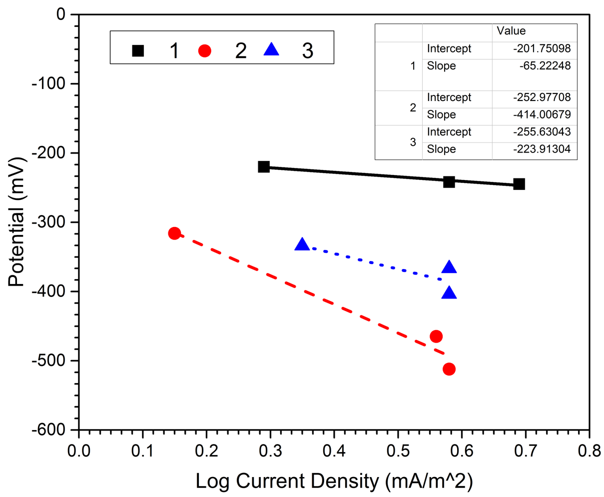

Fig. 8 Cathodic Slope prediction from the potential current graph

Fig. 9 shows the corrosion rate calculated using the modified Butler Volmer equation (Equation 1) with an assumption of β_c to be 120 mV/dec (Fig. 9(a)) and β_c obtained from Fig. 8 (Fig. 9(b)). It can be observed that assumption of β_c being 120 mV/dec constant results in an underestimation of the corrosion rate.

The performance of individual CP zones is also shown in Fig. 9 against published corrosion state as suggested by Concrete Society [17] given in Table 1.

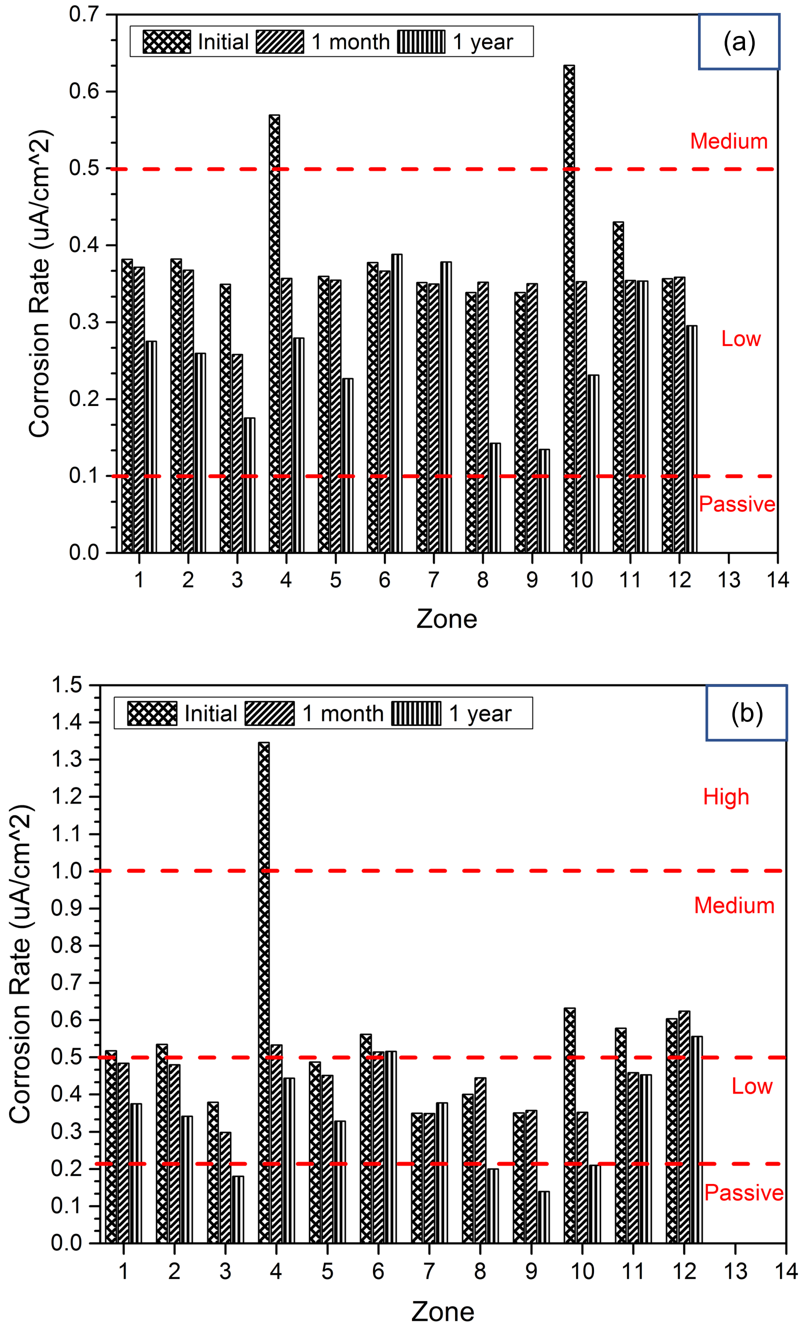

Fig. 9 Corrosion rate for different zones considering cathodic Tafel slope of (a) 120 mV constant, (b) obtained from cathodic slope prediction (Fig. 8)

It can be observed from Fig. 9 that the corrosion rate decreases with time for all the zones and piers. Cathodic protection is observed to be highly effective for zones shown in Fig. 9. For zone 3, 8, 9 and 10 steel moves to passive zone after 1 year of CP application. The largest drop in corrosion rate was observed for zone 8, where corrosion rate dropped by 67% moving steel from highly corrosive to low corrosion state. This shows the effectiveness of CP for piers 1 and 2.

Moreover, for pier 3, steel does not show a significant drop in corrosion rate and steel remains in its initial corrosion state suggesting that it requires longer protection time or increased current output of the zones. Hence, the structure requires longer period of CP application.

Comparing the results from two different analysis methods, it can be clearly seen that the proposed improved method gives an accurate indication of the efficacy of the protection / preventive technique. The standard 100 mV decay criterion has been achieved for all zones. However, proposed method suggests, protection was not achieved for all zones and may require longer protection or increased protection density.

6. Conclusions

The extent of polarisation i.e. negative potential shift induced by the applied current, sufficient to counter the local action anodic current is the measure for assessing the adequacy of an installed CP system. Compliance of the performance criteria, particularly the '100 mV decay' or '100 mV (negative) potential shift', may not be achieved for structures with SACP system however this would not necessarily indicate that the structure is actively corroding; since the application of cathodic protection has an important beneficial effect to alter the surface chemistry of the corroding steel reinforcement. The alternative method of monitoring by using potential shift data obtained from polarization results and by applying a known current density can be used to get an estimation of the corrosion state of steel and the efficiency of the CP using Butler Volmer equation. A decrease in the corrosion rate also indicates that CP is providing effective protection.

Sensitivity analysis using a FEM shows the corrosion rate calculated from the B-V equation is highly dependent on the cathodic Tafel slope and applied current density. Hence, an evaluation of CP performance from corrosion rate estimation requires calculation of cathodic Tafel slope. Corrosion rate estimated from analysing the field data assuming cathodic Tafel slope to be 120 mV/dec constant gives an underestimation of the corrosion rate. Data obtained from the proposed method will be beneficial to the structural engineer for structural assessment. The corrosion rate obtained can be used to estimate the structural capacity of the structure in the long run and its remaining service life.

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Not Applicable

Conflict of Interests

The authors declare that they have no conflict of interest.

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