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Theoretical analysis of the measurement of polarisation resistance in reinforced concrete

Guangling Song *

Department of Mining, Minerals and Materials Engineering, The University of Queensland, St. Lucia, Brisbane, Qld 4072, Australia

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Abstract

Polarisation resistance (R_p) technique based on Stern–Geary equation is one of the most widely used methods of measuring corrosion rate of reinforcement in the field. With the aid of a "sensorised guard ring", this electrochemical technique is claimed to be able to determine corrosion rate (I_{corr}) within a given measuring area. However, there are three theoretical problems in the application of this technique: (1) the original Stern–Geary equation is applicable in a uniform corrosion system at its corrosion potential, whereas the reinforced concrete structure may be subjected to non-uniform corrosion or strong polarisation by macro-cell galvanic effects or imposed currents; (2) the value of the parameter B in the original Stern–Geary equation has been estimated to fall within the range 25–52 mV. This may not be suitable for all the corrosion cases of reinforced concrete structures; (3) The polarised surface area of steel may theoretically not always be fully confined by the sensorised guard ring when the cover concrete is too thick.

This paper aims at discussing the theoretical problems. A general relationship between the dissolution rate of steel reinforcement and the measured polarisation resistance is deduced under general conditions. The range of B value is also analysed based on all the possible corrosion situations of reinforced concrete. Furthermore, unsatisfactory confinement by sensorised guard ring on a thick cover concrete is demonstrated. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Cement; Concrete; Reinforcement; Corrosion; Sensor; Polarisation

1. Introduction

Measurement of polarisation resistance is one of the important electrochemical techniques used for the determination of corrosion rate of steel reinforcement in concrete. The corrosion rate (I_{corr}) is calculated from the polarisation resistance (R_p) using Stern–Geary equation [1], which is expressed as

$$I_{corr} = \frac{B}{R_p}, \tag{1}$$

where B is a constant with a voltage unit and R_p is the polarisation resistance at the corrosion potential corresponding to a unit surface area of reinforcement.

B is determined by cathodic and anodic Tafel slopes $|b_c|$ and $|b_a|$

$$B = \frac{|b_a \cdot b_c|}{|b_a| + |b_c|}. \tag{2}$$

The Tafel slopes are defined by

$$|b_a| = \frac{dE}{d\ln I_a}, \quad |b_c| = -\frac{dE}{d\ln I_c}, \tag{3}$$

where, I_a and I_c are anodic and cathodic reaction rates, respectively.

Theoretically, R_p should be

$$R_p = \left.\frac{dE}{dI_e}\right|_{I_e=0,\, E=E_{corr}}, \tag{4}$$

where I_e is the net electrochemical reaction rate or net polarisation current density of the steel electrode, which is the sum of the polarisation current density (I_p) through the R_p measuring device and the other external current density (I^x) flowing in or out the measuring area due to various effects, such as macro-galvanic current, stray current, cathodic protection/re-alkalisation/desalinsation treatments, etc.

$$I_e = I^x + I_p.$$

Experimentally, R_p can be measured by several methods including ac impedance spectroscopy (EIS),

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[*] Tel.: +61-7-33-65-41-97; fax: +61-7-33-65-38-88.
E-mail address: g.song@minmet.uq.edu.au (G. Song).

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transient techniques, or potentiostatic/galvanostatic measurements, and linear polarisation technique, etc. For the linear polarisation technique, the measured polarisation resistance (R_{pse}) over a measuring surface area (S) of reinforcement is obtained by

$$R_{\mathrm{pse}} = \left.\frac{\mathrm{dE}}{\mathrm{d}i_{\mathrm{p}}}\right|_{i_{\mathrm{p}}=0} \approx \left.\frac{\Delta E}{\Delta i_{\mathrm{p}}}\right|_{i_{\mathrm{p}}=0}, \tag{5}$$

where ΔE is the amplitude of a linearly scanning potential, i_{p} the polarisation current provided by the R_{p} measuring device, and Δi_{p} is the change of the polarisation current responding to ΔE.

When the steel is at its corrosion potential ($E = E_{\mathrm{corr}}$) and there is no other external polarisation current (i^{x}), i.e., $i^{x} = 0$ or $i_{\mathrm{p}} = i_{\mathrm{e}}$, the measured R_{pse} can be related to the theoretical R_{p}

$$\frac{R_{\mathrm{pse}}|_{E=E_{\mathrm{corr}},i^{x}=0}}{S} = R_{\mathrm{p}}. \tag{6}$$

Hence, the corrosion rate can be determined using this $R_{\mathrm{pse}}|E = E_{\mathrm{corr},\, i^{x}=0}$ according to the original Stern–Geary equation (i.e., Eq. (1)) if S and the values of parameter B are known.

Since the polarisation resistance method was established, it has been widely used to estimate corrosion rates of various corroding systems, and its applications and limitations in metal/solution corrosion systems have been discussed [2]. For reinforced concrete corrosion system, with the development of some portable instruments [3,4], this technique has also shown its attractive advantages and is becoming more and more popular. Various researchers [5–10] have reported that the reliability of determining corrosion state of reinforcement in field structures can be improved if polarisation resistance and half-cell potential or resistivity of the cover concrete are used together. For instance, it was claimed [11] that potential mapping may lead to serious misinterpretation in identifying active and passive areas in reinforcement in concrete, whereas R_{p}-based corrosion rate measurement should be more accurate. Nevertheless, in most cases, the original Stern–Geary equation was directly used to calculate corrosion rate of steel in concrete simply assuming that the value of parameter B be within the range 25–52 mV [12–15] and that the calculated corrosion rate can be related to the corrosion situation of steel in concrete according to some proposed criteria [16–19].

However, due to the complexity of reinforced concrete and the theoretical limitations of this electrochemical technique, the use of linear polarisation resistance technique to determine the corrosion rate has the following problems:

(1) The original Stern–Geary equation [1] was derived for a corroding electrode at corrosion potential when $I_{\mathrm{p}} = 0$ and $I^{x} = 0$, without considering the influence of non-uniform distribution of anodic and cathodic reactions. This equation should be applicable for a non-polarised uniform corrosion system. Unfortunately, non-uniform corrosion under polarisation by macro-cell effects or imposed currents is common in practical reinforced concrete systems [20]. So direct application of the original Stern–Geary equation to such reinforced concrete systems may be unreasonable. So far, such a concern has not been shown in the relevant literature. In the published work, the original Stern–Geary equation was usually used without questioning the corrosion forms (uniform or non-uniform) or polarisation conditions (at corrosion potential or not), and unreasonable results were sometimes obtained [21,22]. González et al. [11] measured the corrosion rates of active and passive steel bars coupled in a concrete beam by using a confined R_{p} technique. Their results showed that the cathodic (passive) steel bar coupled with the anodic (active) steel bar had a relatively high corrosion rate, compared with the corrosion rate of the cathodic steel bar when it was not connected with the anodic bar. This is theoretically incorrect, because due to galvanic effect of the coupled steel bars, the cathode was cathodically polarised by the anode, so its corrosion rate should be reduced after it was connected to the anode.

(2) A value range of parameter B (25–52 mV) has been suggested [12–14] for the original Stern–Geary equation being used in a reinforced concrete system. It was claimed that a given value of B within this range would lead to a relative error of two in the determination of corrosion rate [23,24]. However, the proposed value range of B is mainly based on simple corrosion conditions (passive or active steel reinforcement around its corrosion potential). In practice, the corrosion situations are more complicated. The steel reinforcement could be locally corroded, or polarised by macro-galvanic currents or stray currents, or under cathodic protection, etc.; also, the cathodic oxygen reduction could be under diffusion control or active reaction control. Whether the proposed B value is suitable for those complicated corrosion cases has not been carefully discussed.

(3) For concrete structures in the field, the true polarised surface area of reinforcement during measurement is unknown. To solve such a problem, a number of approaches have been tried in the laboratory and in the field [25]. The best idea is to control the distribution of current density and make it uniform along the reinforcing bar during the measurement of R_{p}. One of the techniques, which is used to achieve this purpose, is known as sensorised guard ring [26–29]. It is the most advanced of those developed so far [4], and in many cases it can successfully confine the polarisation area. However, in some cases, e.g., when the cover concrete is too thick, the confinement of the polarisation area may

not be achieved. Flis et al. [30] used numerical technique to determine the influences of various parameters, including the cover thickness, on the current distribution in reinforced concrete. They concluded that the polarisation area increased significantly with increasing cover thickness. However, the influence of cover thickness on the confinement effectiveness of the sensorised guard ring has not been widely realised, and more detailed theoretical illustration is still needed in this area.

In addition, the IR drop is also a problem in the measurement due to the high resistivity of concrete. However, this issue seems to have been realised and considered, because IR drop compensation technique has been widely adopted in recently developed equipment. It is believed that this problem will become less serious with the development of instrument in future, and thereby this issue will not be particularly addressed in this paper.

A general relationship between the corrosion rate and measured polarisation resistance is undoubtedly necessary for the corrosion rate determination of a reinforced concrete which could be uniformly or non-uniformly corroding under polarisation or non-polarisation conditions. It is also important to be aware of the possibilities that errors could be caused by using an inappropriate parameter B. In field measurement using a sensorised guard ring, understanding the influence of cover thickness on the confinement of the sensorised guard ring device would be of great help for obtaining a reliable measured R_p. This paper attempts to address these issues. It is hoped that the theoretical discussion can be of assistance in explanation of some experimental phenomena.

2. Relationship between the measured polarisation resistance and dissolution rate of steel

Generally, within a selected measuring area, the anodic and cathodic reactions rarely occur uniformly along the reinforcing steel in concrete because of the heterogeneity of concrete. The anodic process is stronger than the cathodic reaction in anodic zones, while the latter is dominant over the anodic one in cathodic zones. The anodic and cathodic zones could be well separated, or merged together without a distinct border. In addition, both anodic and cathodic zones may still be influenced by currents coming from the areas other than the measuring region, e.g., provided by remote anodic or cathodic reactions through macro-cell effect, or imposed by cathodic protection, de-salinisation, or re-alkalisation treatment.

Fig. 1 schematically illustrates all the possible currents affecting the measuring area S. The polarisation current i_p provided by the R_p measurement sensor is only confined within this area, where there are coexisting anodic and cathodic zones whose surface areas are denoted as S^a and S^c, respectively. Anodic and cathodic reaction rates in S^a, represented by current densities, are I_a^a and I_c^a; and current densities I_a^c and I_c^c stand for the anodic and cathodic reaction rates in S^c. In principle, there should be

$$I_a^a > I_c^a, \quad I_a^c < I_c^c.$$

In the steady state, the overall net electrochemical reaction rate (net polarisation current) i_e over area S is mainly contributed from I_a^a, I_c^a, I_a^c and I_c^c in S^a and S^c,

$$i_e = S^a(I_a^a - I_c^a) + S^c(I_a^c - I_c^c) = i_a - i_c, \tag{7}$$

where i_a and i_c are the total rates of anodic and cathodic reactions, respectively, over the measuring area

$$i_a = (S^a I_a^a + S^c I_a^c), \quad i_c = (S^a I_c^a + S^c I_c^c). \tag{8}$$

So, the average anodic and cathodic current densities, I_a and I_c, over the measured area S can be written as

$$\begin{aligned} I_a &= i_a/S = I_a^a S^a/S + I_a^c S^c/S, \\ I_c &= i_c/S = I_c^a S^a/S + I_c^c S^c/S. \end{aligned} \tag{9}$$

On the other hand, during the measurement, the polarisation current i_p through the R_p sensor can affect i_e, because $i_e = i_p + i^x$. Hence

$$i_p = i_e - i^x = i_a - i_c - i^x. \tag{10}$$

The measured polarisation resistance, R_{pse}, of reinforcement over the measuring area S, can be obtained by substituting Eq. (10) into (5)

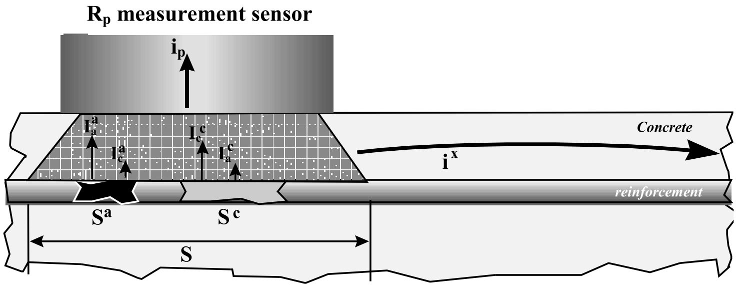


Fig. 1. Schematic representation of polarisation of reinforced concrete.

$$\frac{1}{R_{\mathrm{pse}}} = \left.\frac{\mathrm{d}i_{\mathrm{p}}}{\mathrm{d}E}\right|_{i_{\mathrm{p}}=0} = \left[\frac{\mathrm{d}i_{\mathrm{a}}}{\mathrm{d}E} - \frac{\mathrm{d}i_{\mathrm{c}}}{\mathrm{d}E} - \frac{\mathrm{d}i^{\mathrm{x}}}{\mathrm{d}E}\right]_{i_{\mathrm{p}}=0}. \tag{11}$$

The variation of E or i_{p} within S has little effect on the external current i^{x} from outside of the measuring area S, i.e., i^{x} is independent of E:

$$\mathrm{d}i^{\mathrm{x}}/\mathrm{d}E \rightarrow 0. \tag{12}$$

So Eq. (11) can be re-written into

$$\frac{1}{R_{\mathrm{pse}}} = \left[\frac{\mathrm{d}i_{\mathrm{a}}}{\mathrm{d}E} - \frac{\mathrm{d}i_{\mathrm{c}}}{\mathrm{d}E}\right]_{i_{\mathrm{p}}=0} = \left[\frac{i_{\mathrm{a}}}{i_{\mathrm{a}}}\frac{\mathrm{d}i_{\mathrm{a}}}{\mathrm{d}E} - \frac{i_{\mathrm{c}}}{i_{\mathrm{c}}}\frac{\mathrm{d}i_{\mathrm{c}}}{\mathrm{d}E}\right]_{i_{\mathrm{p}}=0}$$
$$= \left[i_{\mathrm{a}}\frac{\mathrm{d}\ln i_{\mathrm{a}}}{\mathrm{d}E} - \frac{i_{\mathrm{c}}\mathrm{d}\ln i_{\mathrm{c}}}{\mathrm{d}E}\right]_{i_{\mathrm{p}}=0}. \tag{13}$$

Let

$$|\overline{b}_{\mathrm{a}}| = \frac{\mathrm{d}E}{\mathrm{d}\ln i_{\mathrm{a}}} = \frac{\mathrm{d}E}{\mathrm{d}\ln(S^{\mathrm{a}}I^{\mathrm{a}}_{\mathrm{a}} + S^{\mathrm{c}}I^{\mathrm{c}}_{\mathrm{a}})}, \tag{14}$$

$$|\overline{b}_{\mathrm{c}}| = -\frac{\mathrm{d}E}{\mathrm{d}\ln i_{\mathrm{c}}} = -\frac{\mathrm{d}E}{\mathrm{d}\ln(S^{\mathrm{a}}I^{\mathrm{a}}_{\mathrm{c}} + S^{\mathrm{c}}I^{\mathrm{c}}_{\mathrm{c}})}, \tag{15}$$

we have

$$\frac{1}{R_{\mathrm{pse}}} = \left[\frac{i_{\mathrm{a}}}{|\overline{b}_{\mathrm{a}}|} + \frac{i_{\mathrm{c}}}{|\overline{b}_{\mathrm{c}}|}\right]_{i_{\mathrm{p}}} \tag{16}$$

or

$$R_{\mathrm{pse}} = \left[\frac{|\overline{b}_{\mathrm{a}} \cdot \overline{b}_{\mathrm{c}}|}{i_{\mathrm{a}}|\overline{b}_{\mathrm{c}}| + i_{\mathrm{c}}|\overline{b}_{\mathrm{a}}|}\right]_{i_{\mathrm{p}}=0}. \tag{17}$$

The electrochemical reactions in S^{a} and S^{c} have contributions to both $|\overline{b}_{\mathrm{a}}|$ and $|\overline{b}_{\mathrm{c}}|$. In this paper, $|\overline{b}_{\mathrm{a}}|$ and $|\overline{b}_{\mathrm{c}}|$ are particularly termed as combined anodic and cathodic Tafel slopes, to distinguish them from the normal Tafel slopes $|b_{\mathrm{a}}|$ and $|b_{\mathrm{c}}|$ (Eq. (3)). In the case of $I^{\mathrm{c}}_{\mathrm{a}} \rightarrow 0$ and $I^{\mathrm{a}}_{\mathrm{c}} \rightarrow 0$, $|\overline{b}_{\mathrm{a}}|$ and $|\overline{b}_{\mathrm{c}}|$ will degenerate back to the normal Tafel slopes.

The anodic dissolution rate (i_{a}) is responsible for the reduction of cross-section of reinforcing bar in the measuring zone. In this sense, it can also be termed as dissolution or corrosion rate (i_{corr}) of reinforcement in concrete. Thus, from Eqs. (16) or (17), we have the dissolution rate (i_{corr}) of reinforcing steel

$$i_{\mathrm{corr}} = \frac{\overline{B}_{\mathrm{e}}}{R_{\mathrm{pse}}}, \tag{18}$$

where

$$\overline{B}_{\mathrm{e}} = |\overline{b}_{\mathrm{a}}|\left(1 - i_{\mathrm{c}}\frac{R_{\mathrm{pse}}}{|\overline{b}_{\mathrm{c}}|}\right). \tag{19}$$

Eq. (18) describes the general relationship between the measured polarisation resistance and the corrosion rate of reinforcement within the measuring zone, in which $\overline{B}_{\mathrm{e}}$ is actually dependent on i^{x} or E, not a constant as B in the original Stern–Geary equation. With the increase of potential or decrease of i_{c}, $\overline{B}_{\mathrm{e}}$ could vary from 0 to $|\overline{b}_{\mathrm{a}}|$ that could be an infinity for a passive steel.

In some particular cases, relationships (18) and (19) could be further simplified. For instance, there are two extreme cases for the influences of the remote polarisation on area S: very strong ($|i^{\mathrm{x}}| \gg 0$) or very weak ($i^{\mathrm{x}} \rightarrow 0$). In terms of the distribution of anodic and cathodic reactions within zone S, there are two extreme cases too, i.e., completely uniform or completely separated. These special situations and corresponding equations are summarised in Table 1.

In summary, the relationship between the corrosion rate and the measured polarisation resistance strongly depends on the corrosion situations. Even though it can apparently be written into a formula (e.g., Eq. (18)) similar to the original Stern–Geary equation, but the parameter $\overline{B}_{\mathrm{e}}$ involved in the equation is not a constant and has a broader definition and a wider range of value (see Eq. (19)). The original Stern–Geary equation is only a special form of this equation valid under particular conditions.

In fact, the above theoretical inference has been observed in experiments. Bertocci [21] has noticed that the measured polarisation resistance appears to decrease by anodic or cathodic polarisation. Thompson et al. [22] also found that in the vicinity of macro-cell couples, polarisation resistance overestimated the corrosion rate in the non-corroding areas. They experimentally realised that in the presence of cathodic protection, the polarisation resistance is no longer related to the corrosion rate, but related to the amount of cathodic current being applied to the steel specimen. Their feeling about the measured polarisation resistance in that case was actually a reflection of the theoretical equation of cases (1-1-c), (2-1-c) and (3-1-c) developed in this paper.

3. Estimate of parameter $\overline{B}_{\mathrm{e}}$

3.1. In case of $\overline{B}_{\mathrm{e}} = B$

This is the simplest case when the original Stern–Geary equation is applicable. From the electrochemical point of view, the polarisation of a reinforcement in concrete could have four possiblities (Fig. 2):

Possibility (*A*) $|b_{\mathrm{a}}| \ll \infty$, $|b_{\mathrm{c}}| \ll \infty$: Neither the reinforcing steel is in a passive state, nor the supply and transport of oxygen in concrete is controlling the corrosion reaction of the steel. This could occur when: (1) the concrete has been carbonated and the pH value of the pore solution in the vicinity of the steel is lower than 9; or (2) there is sufficient supplies of oxygen and considerable chloride ions, whose concentration is higher than the "critical threshold" in the vicinity of the

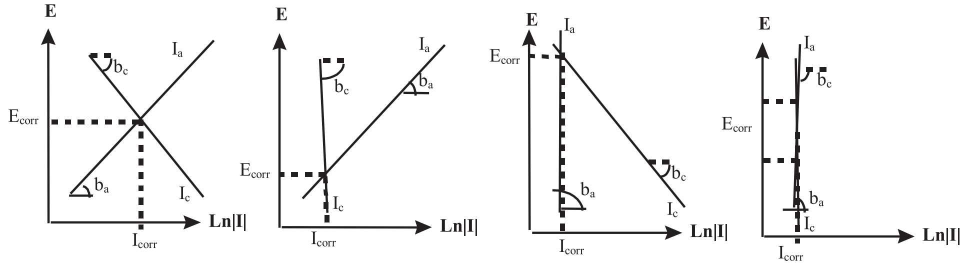
Table 1
Theoretical relationship between corrosion rate and measured polarisation resistance for various types of corrosion under different polarisation conditions

Polarisation conditions	Corrosion types		
	Any type of corrosion within measuring area	Localised corrosion (incl. pitting corrosion) or non-uniform corrosion (incl. galvanic corrosion) within measuring area	Uniform corrosion within measuring area
Strong external anodic polarisation (e.g. being attacked by stray currents, or influenced by galvanic effects from other areas)	*Case (1-1-a)* $i_{\mathrm{corr}} = \overline{B}_{\mathrm{ea}}/R_{\mathrm{pse}}$, $\overline{B}_{\mathrm{ea}} = \lvert\overline{b}_{\mathrm{a}}\rvert$	*Case (2-1-a)* $i_{\mathrm{corr}} = B_{\mathrm{ea}}/R_{\mathrm{pse}}$, $B_{\mathrm{ea}} = \lvert b_{\mathrm{a}}\rvert$	*Case (3-1-a)* $i_{\mathrm{corr}} = B_{\mathrm{ea}}/R_{\mathrm{pse}}$, $B_{\mathrm{ea}} = \lvert b_{\mathrm{a}}\rvert$
Strong external cathodic polarisation (e.g. under cathodic protection, or being desalinisation/re-alkalisation treated, attacked by stray currents, or influenced by galvanic effects from other areas)	*Case (1-1-c)* $i_{\mathrm{corr}} = \overline{B}_{\mathrm{ec}}/R_{\mathrm{pse}} \to 0$, $\overline{B}_{\mathrm{ec}} \to 0$ or $R_{\mathrm{pse}} = \lvert\overline{b}_{\mathrm{c}}\rvert/i_{\mathrm{c}} = -\lvert\overline{b}_{\mathrm{c}}\rvert/i^{\mathrm{x}}$	*Case (2-1-c)* $i_{\mathrm{corr}} = B_{\mathrm{ec}}/R_{\mathrm{pse}} \to 0$, $B_{\mathrm{ec}} \to 0$ or $R_{\mathrm{pse}} = \lvert b_{\mathrm{c}}\rvert/i_{\mathrm{c}} = -\lvert b_{\mathrm{c}}\rvert/i^{\mathrm{x}}$	*Case (3-1-c)* $i_{\mathrm{corr}} = B_{\mathrm{ec}}/R_{\mathrm{pse}} \to 0$, $B_{\mathrm{ec}} \to 0$ or $R_{\mathrm{pse}} = \lvert b_{\mathrm{c}}\rvert/i_{\mathrm{c}} = -\lvert b_{\mathrm{c}}\rvert/i^{\mathrm{x}}$
Weak or no external polarisation (e.g. around corrosion potential)	*Case (1-2)* $i_{\mathrm{corr}} = \overline{B}/R_{\mathrm{ps}}$, $\overline{B} = \lvert\overline{b}_{\mathrm{a}}\rvert\lvert\overline{b}_{\mathrm{c}}\rvert/(\lvert\overline{b}_{\mathrm{a}}\rvert + \lvert\overline{b}_{\mathrm{c}}\rvert)$	*Case (2-2)* $i_{\mathrm{corr}} = B/R_{\mathrm{ps}}$, $B = \lvert b_{\mathrm{a}}\rvert \cdot \lvert b_{\mathrm{c}}\rvert/(\lvert b_{\mathrm{a}}\rvert + \lvert b_{\mathrm{c}}\rvert)$	*Case (3-2)* $i_{\mathrm{corr}} = B/R_{\mathrm{ps}}$, $B = \lvert b_{\mathrm{a}}\rvert \cdot \lvert b_{\mathrm{c}}\rvert/(\lvert b_{\mathrm{a}}\rvert + \lvert b_{\mathrm{c}}\rvert)$

reinforcing steel. The polarisation behaviour of this type of corrosion system can be illustrated in Fig. 2(a), which has normally an intermediate corrosion potential (E_{corr}).

In a basic solution like NaOH with pH > 13 at 20°C, the anodic Tafel slope $|b_{\mathrm{a}}|$ of iron is only 13–17 mV [31]. Hence, for steel in concrete, an approximate anodic Tafel slope $|b_{\mathrm{a}}|$ with a value of about 13–17 mV could be a reasonable estimate. For the cathodic processes in a reinforced concrete, the main cathodic process should be the reduction of oxygen; while the hydrogen evolution could also have an appreciable contribution to the cathodic process in some local areas at the surface of the reinforcing steel in a carbonated concrete. The cathodic Tafel slope $|b_{\mathrm{a}}|$ for hydrogen evolution on iron in NaOH solutions is about 52–65 mV [32]. Oxygen reduction was found to have a cathodic Tafel slope varying with the pH value of the solution [33], and could change from 52 to 21 mV. Therefore, considering the probable hydrogen evolution and oxygen reduction, a reasonable estimate of $|b_{\mathrm{a}}|$ could range from 21 to 65 mV. In summary, we could have $13\ \mathrm{mV} \leqslant |b_{\mathrm{a}}| \leqslant 17\ \mathrm{mV}$ and $21\ \mathrm{mV} \leqslant |b_{\mathrm{c}}| \leqslant 65\ \mathrm{mV}$. According to Eq. (2), parameter B could be approximately within the range of 8–13.5 mV ($8\ \mathrm{mV} < B < 13.5\ \mathrm{mV}$).

Possibility (*B*) $|b_{\mathrm{a}}| \ll \infty$, $|b_{\mathrm{c}}| \to \infty$: The steel rebar is not in its passive state and the diffusion of oxygen in concrete is the rate determining step controlling the corrosion reaction. This could most probably occur in a water-saturated and chloride-polluted but uncarbonated concrete, in which the supply of oxygen is limited, but chloride concentration considerably higher than the critical threshold has reached the vicinity of the reinforcing steel. Steel in such a concrete could have various corrosion rates, depending on the supply rate of oxygen



(A) $b_a << +\infty$, $b_c >> -\infty$ (B) $b_a << +\infty$, $b_c \to -\infty$ (C) $b_a \to +\infty$, $b_c >> -\infty$ (D) $b_a \to +\infty$, $b_c \to -\infty$

Fig. 2. Four different possible polarisation behaviours of steel in concrete.

in the concrete. Its polarisation behaviour is demonstrated in Fig. 2(b), and its corrosion potential is relatively negative. A more negative corrosion potential (also a more negative half-cell potential) in this case would mean a lower corrosion rate of the steel reinforcement. It does not follow the ASTM C867 standard about the half-cell potential indicator of corrosion risk in RC.

If this possible case occurs, then the anodic Tafel slope ($|b_a|$) could fall in a range similar to that in case (A), i.e., $13\ \text{mV} \leqslant |b_a| \leqslant 17\ \text{mV}$. However, the oxygen diffusion-controlled cathodic reaction would have a very high Tafel slope, $|b_a| \to \infty$. So, parameter B could be roughly equal to the anodic Tafel slope $|b_a|$ according to Eq. (2), ranging from 13 to 17 mV ($13\ \text{mV} < B < 17\ \text{mV}$).

Possibility (*C*) $|b_a| \to \infty, |b_c| \ll \infty$: The supply of oxygen in concrete is sufficient and the steel is at its passive state. It can occur in an uncarbonated and relatively dry concrete whose chloride content in the vicinity of the reinforcement is negligible or much less than the critical threshold. The polarisation behaviour of the steel in this concrete is shown in Fig. 2(c), whose corrosion potential is relatively high. The higher the corrosion potential (also the higher half-cell potential), the better the steel is protected by the passive film and the lower the corrosion risk, which is consistent with the ASTM C867 standard.

The anodic Tafel slope for a passivated metal is normally assumed to have an infinite value, i.e., $|b_a| \approx \infty$. The cathodic reaction is mainly oxygen reduction, so $|b_a|$ could be around 21–52 mV as discussed in possibility (A). Therefore, we could have $B \approx |b_c| \approx 21 \sim 52\ \text{mV}$ according to Eq. (2) ($21\ \text{mV} < B < 52\ \text{mV}$).

Possibility (*D*) $|b_a| \to \infty$, $|b_c| \to \infty$: The steel in concrete is in its passive state while the cathodic reaction is under the control of oxygen diffusion. It might occur on a passive reinforcement in wet concrete, because the following equation could be held in this occasion:

$$I_{pa} \approx |I_d| = 4FD_0C_0/L, \tag{20}$$

where F is the Faraday constant, L the thickness of the cover concrete, C_0 the concentration of oxygen in the concrete, D_0 the oxygen diffusion coefficient, I_d the limited diffusion current density of oxygen in the concrete, and I_{pa} is the passivation current density of the passivated reinforcement. All the parameters could widely vary in field conditions. The possibility for relationship (20) to be held would be high in practice. In fact, absolute values of the anodic and cathodic Tafel slopes sometimes both higher than 500 mV have been shown in Bertocci's study [21] on inhibitors in highway deicers.

The polarisation behaviour of a passive steel reinforcement under oxygen diffusion control is displayed in Fig. 2(d). The corrosion potential, E_{corr}, of such a system would not be very stable, and could drift over a relatively wide range. A very small variation in I_{pa} or I_d could lead to a dramatic shift in potential. Since both b_a and b_c are nearly infinite, parameter B would also approach infinity ($B \to \infty$).

Therefore, in case of $\overline{B}_e = B$, a reasonable estimate of parameter B should be based on all the four possibilities, and a conservatively estimated range for B should be from 8 to ∞ mV. This range is much wider than the currently used one (25–52 mV). It means that an infinite relative error might be induced if a B value within the range 25–52 mV is used in the calculation of the corrosion rate. Furthermore, in case of $I_{corr} \approx I_{pa} \approx |I_d|$, $R_p \to \infty$, if a B value within 25–52 mV is still used to calculate the corrosion rate, then a zero corrosion rate would be obtained. This would not be a true representation of the corrosion rate.

3.2. In case of $\overline{B}_e \neq B$

In this case the original Stern–Geary equation is not applicable, $\overline{B}_e$ is equal to $|\overline{b}_a| \cdot |\overline{b}_c|/(|\overline{b}_a| + |\overline{b}_c|)$, which could change from 0 to ∞ depending on the external polarisation and corrosion types of the steel. Therefore, the use of the typical value range of B (25–52 mV) could lead to more significant theoretical error in the calculation of corrosion rate of reinforcement.

4. Confinement of sensorised guard ring

The principle of the sensorised guard ring is schematically demonstrated in Fig. 3. The key point is that if the distribution of current lines between the steel bar and the sensorised guard ring device on the concrete surface were uniform, then the potentials E_1 and E_2 at the points r_1 and r_2 on the surface of the concrete, measured by sensors R_1 and R_2, would be equal. Therefore, during the measurement of R_p, the condition $E_1 = E_2$ is achieved by adjusting the confining current through the guard ring (GR), so that the distribution of current lines between the steel bar and the device on the concrete surface would become uniform, as illustrated in Fig. 3.

The above idea appears to be reasonable. However, in some cases, e.g., the cover concrete is too thick, it would be difficult for the i_p applied through the CE to be confined within the area from X to Y (Fig. 3).

For simplicity, in the following analysis, it is assumed that the reinforcement is uniformly corroding, and the cover concrete is also completely uniform. Furthermore, the "guard ring" is also simplified such that the diameter of its central counter electrode is equal to the width of the confining ring. This is a simple ideal case, and it

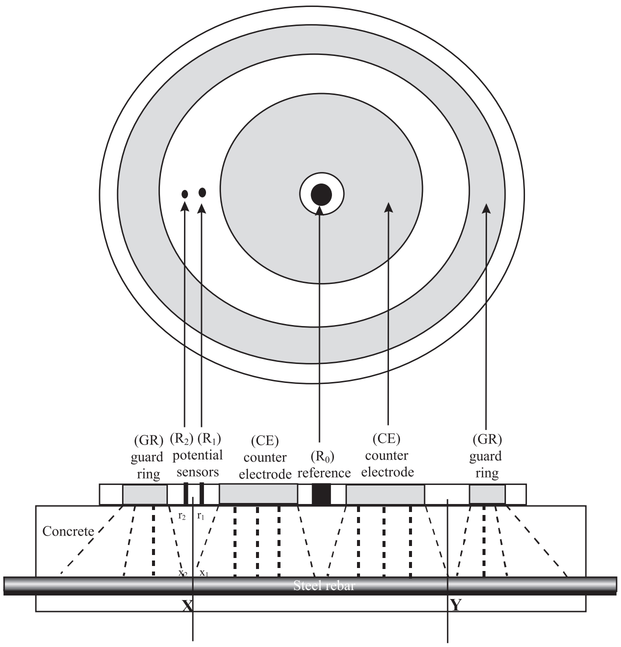


Fig. 3. Schematic diagram of sensorised guard ring.

should theoretically be the easiest case for achieving full confinement. If the confinement is still unsatisfactory in such a simple and ideal case, then in realistic cases in the field, the confinement would be more difficult to achieve.

Under the above ideal condition of a uniform corrosion of steel rebar in a uniform concrete matrix, E_1 and E_2 would be equal, if the confining current density applied through the GR is equal to the polarisation current density (I_p) applied through the central counter electrode (CE), or if the potential of GR is the same as the applied potential on the CE. Only under these conditions (i.e., $E_1 = E_2$), could the polarisation current (i_p) applied through the CE be expected to be distributed within the area from X to Y along the steel bar (see Fig. 3).

Fig. 4 schematically presents the distribution of current densities in a thick cover concrete under a sensorised guard ring device. The area of each shadow represents the total current passing through this area. Therefore, the shadow enclosed by FHJI ($\mathbf{A}_{\mathrm{FHJI}}$) represents the polarisation current (i_p) passing through the CE.

According to the distribution of current densities in Fig. 4, we have

$$i_p = \mathbf{A}_{\mathrm{FHJI}}, \tag{21}$$

which can be further decomposed into the sum of smaller areas

$$i_p = \mathbf{A}_{\mathrm{IFHJ}} = \mathbf{A}_{\mathrm{IEXYGJ}} + \mathbf{A}_{\mathrm{EFX}} + \mathbf{A}_{\mathrm{GYH}}. \tag{22}$$

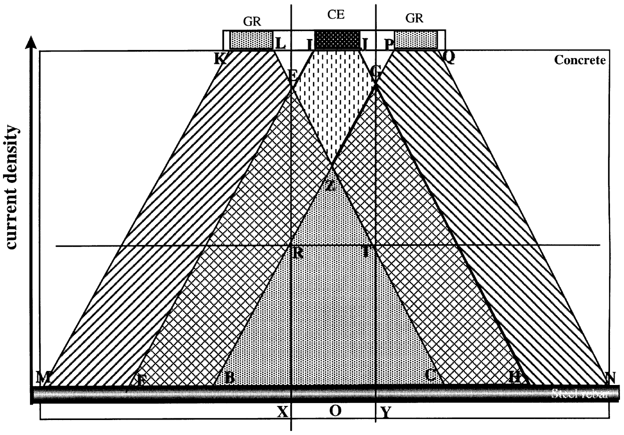


Fig. 4. Schematic presentation of the distribution of current density under sensorised guard ring device.

On the other hand, i_{XY} can be considered to be composed of those parts of the i_p applied through the CE and the confining current provided by the GR, passing through the area X–Y of the rebar. In Fig. 4, it can be expressed as the sum of the overlapped shadow areas above the area X–Y

$$i_{\mathrm{XY}} = \mathbf{A}_{\mathrm{IEXYGJ}} + \mathbf{A}_{\mathrm{EXYT}} + \mathbf{A}_{\mathrm{GRXY}} \tag{23}$$

If i_p is completely confined within the area X–Y, then the total current (i_{XY}) passing through the area X–Y on the rebar would be equal to i_p, i.e., $i_p = i_{\mathrm{XY}}$, or $i_p - i_{\mathrm{XY}} = 0$. According to Eqs. (22) and (23), we have

$$i_p - i_{\mathrm{XY}} = [\mathbf{A}_{\mathrm{EFX}} + \mathbf{A}_{\mathrm{GYH}}] - [\mathbf{A}_{\mathrm{EXYT}} + \mathbf{A}_{\mathrm{GRXY}}]. \tag{24}$$

If $[\mathbf{A}_{\mathrm{EFX}} + \mathbf{A}_{\mathrm{GYH}}] = [\mathbf{A}_{\mathrm{EXYT}} + \mathbf{A}_{\mathrm{GRXY}}]$, a 100% confinement can be reached, and the accurate R_p be measured; if $[\mathbf{A}_{\mathrm{EFX}} + \mathbf{A}_{\mathrm{GYH}}] > [\mathbf{A}_{\mathrm{EXYT}} + \mathbf{A}_{\mathrm{GRXY}}]$, then i_p cannot be fully confined by the sensorised guard ring, which would lead to an underestimated R_p; if $[\mathbf{A}_{\mathrm{EFX}} + \mathbf{A}_{\mathrm{GYH}}] < [\mathbf{A}_{\mathrm{EXYT}} + \mathbf{A}_{\mathrm{GRXY}}]$, then i_p is overconfined, and as a result, the R_p would be overestimated.

The thickness of cover concrete is a very important parameter affecting the confinement. Generally speaking, $[\mathbf{A}_{\mathrm{EFX}} + \mathbf{A}_{\mathrm{GYH}}]$ is not necessary always equal to $[\mathbf{A}_{\mathrm{EXYT}} + \mathbf{A}_{\mathrm{GRXY}}]$. Based on the earlier assumption of uniform concrete and corrosion, we should have

$$\mathbf{A}_{\mathrm{EFX}} = \mathbf{A}_{\mathrm{EXC}} \quad \text{and} \quad \mathbf{A}_{\mathrm{GYH}} = \mathbf{A}_{\mathrm{GBY}}.$$

So,

$$\begin{aligned} i_p - i_{\mathrm{XY}} &= [\mathbf{A}_{\mathrm{EXC}} - \mathbf{A}_{\mathrm{EXYT}}] + [\mathbf{A}_{\mathrm{GBY}} - \mathbf{A}_{\mathrm{GRXY}}] \\ &= \mathbf{A}_{\mathrm{TYC}} + \mathbf{A}_{\mathrm{RBX}} > 0, \end{aligned} \tag{25}$$

i.e., $i_p \neq i_{\mathrm{XY}}$, or $i_p > i_{\mathrm{XY}}$. This means that the polarisation current i_p cannot be completely confined within area X–Y in this case. However, if a steel bar is embedded in a concrete shallower than the level R–T, then complete confinement could be achieved, because $[\mathbf{A}_{\mathrm{EFX}} + \mathbf{A}_{\mathrm{GYH}}] = [\mathbf{A}_{\mathrm{EXYT}} + \mathbf{A}_{\mathrm{GRXY}}]$ would be held in this case.

In practice, the distribution of current densities under the device is more complicated than Fig. 4. For example, due to the heterogeneity of the cover concrete, when the confine current becomes more spread than i_p (in other words, lines L–C and P–B in Fig. 4 have much smaller angles to line L–P than lines I–F and J–H), then $[\mathbf{A}_{EFX} + \mathbf{A}_{GYH}] < [\mathbf{A}_{EXYT} + \mathbf{A}_{GRXY}]$ would be possible, and i_p may be overconfined, leading to overestimated R_p.

In addition, the resistivity of concrete can also affect the confinement of the guard ring in a similar manner. For example, low resistivity of concrete has the effect of spreading the current over a large area, leading to $[\mathbf{A}_{EFX} + \mathbf{A}_{GYH}] > [\mathbf{A}_{EXYT} + \mathbf{A}_{GRXY}]$, so that effective confinement is difficult to be achieved by the sensorised guard ring. Therefore, the guard ring is unlikely to be successfully used on a reinforced concrete immersed in water or completely water saturated.

All the factors that can change the distributions of currents [30] in a concrete and consequently change the areas of $\mathbf{A}_{EFX}$, $\mathbf{A}_{EXYT}$, $\mathbf{A}_{GYH}$ and $\mathbf{A}_{GRXY}$ would also affect the confinement effect of the sensorised guard ring. These factors include potential and confining current density of GR, width of GR, diameter of CE, spacing between GR and CE, contact resistance between GR/concrete and CE/concrete, delamination and cracking of the cover concrete, porosity and heterogeneity of concrete, insulate coating on the concrete surface, polarisation resistance at the interface between steel bar and concrete, position of counter electrode, interference of stray currents or galvanic currents, etc. They can either increase or decrease the confinement, and result in underestimated or overestimated values of R_p.

In the measurement of R_p on an existing reinforced structure, the cover thickness, i.e., the depth at which the steel is embedded, cannot be changed. To obtain realistic measurements, factors that affect the corrosion rate of reinforcement, such as resistivity of concrete, should not be changed (e.g., by wetting), otherwise the measured results would not reflect the true corrosion rate under the natural conditions. To achieve a better confinement effect, the best option might be to modify the parameters of the sensorised guard ring, such as the width of GR, the diameter of CE, the spacing between GR and CE, and the confining current density through the GR, etc. According to Fig. 4, an instrument in which the spacing between GR and CE can be increased for thicker cover concretes might be an option to improve the confinement of the current density (in this case, the defined confinement area is enlarged).

5. Concluding remark

The original Stern–Geary equation is only a special relationship between the measured polarisation resistance and corrosion rate under special (non-polarisation and uniform) corrosion conditions. The general equation for all types of corrosion under any polarisation condition is different from the original Stern–Geary expression. The Stern–Geary equation can only be used in limited corrosion cases. Misusing it in other cases could introduce significant errors.

In the case that the Stern–Geary equation is applicable, the typical value of parameter B (25–52 mV) is not acceptable for all corrosion cases. Particularly when the passivated steel reinforcement has a diffusion-controlled cathodic process, the value of parameter B could become extremely high.

Even in the case that the Stern–Geary equation is applicable and the typical value (25–52 mV) of parameter B is acceptable, significant errors could still be introduced to the calculated corrosion rate due to the overconfinement or underconfinement effect of the sensorised guard ring. A full confinement may not be achieved if the cover concrete is too thick.

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