



# Measurement of corrosion in soil using the galvanostatic pulse technique



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## ARTICLE INFO

### Article history:

Received 20 August 2013

Accepted 29 November 2013

Available online 5 December 2013

### Keywords:

- A. Iron
- B. Galvanostatic
- B. Polarisation
- C. Interfaces

## ABSTRACT

The galvanostatic pulse technique was applied in the soil environment, allowing the characterisation of corrosion rate and the double layer capacitance formed at the metal/soil interface. A well-controlled laboratory framework for assessing potential corrosivity amongst different soil samples was presented. The galvanostatic pulse technique and the suggested framework were used to evaluate the effect of varying clay and chloride contents on corrosion of common ferrous pipeline alloys. A coupled moisture-chloride effect induced by clay was used to explain the features of the electrical double layer. The study provides a reference for calibrating future corrosion experiments in soil media.

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## 1. Introduction

The ageing of pipelines, in addition to any unanticipated accelerated deterioration, presents a serious engineering problem [1,2]. For efficient asset management, investigations into soil properties and their relation to corrosion are essential. Apart from the general classification schemes ([2–4] and the references therein) to identify potentially corrosive soils, there has been considerable interest in predicting the corrosion rates [5–8] of pipelines in soils. The ASTM G162–99 [9] standard describes procedures for conducting and evaluating laboratory corrosion tests in soils. The procedure is based on laboratory weight loss measurements of test specimens embedded in saturated soil samples and monitored over a sufficient exposure time, which can result in lengthy exposure periods for meaningful results. Laboratory tests for estimating corrosion rates now include electrochemical methods [6,10,11] some of which are non-destructive techniques (NDT). One common NDT is the linear polarisation resistance (LPR) method [12]. Albeit, the drawbacks in using LPR techniques are well known [13], it is still utilised for estimating corrosion rates and assessing soil corrosivity under both laboratory and *in situ* field conditions [14–16]. Presently no electrochemical technique and accompanying procedures have been adopted as standards for conducting corrosion tests in soils, thereby making it an active area of research.

Prior studies report measurement of various soil properties and their corresponding effects on corrosion [17–19]. Some studies have discussed water content, which directly affects soil resistivity,

a major factor in overall corrosion [20,21]. In other studies the soil moisture level was maintained at a specific level [22] or controlled through external injections [23]. However, the homogeneity of water distribution in the soil can be very difficult to control. Following Gupta and Gupta [20], the notion of <25% w/w of moisture content in soils has been suggested as the moisture level for maximum corrosion in some works [24,25]. However, a usual oversight are the Atterberg Limits [26], which categorise the four different states of soil depending upon the water content; solid, semi-solid, plastic, and liquid. The procedure used to saturate soils and their subsequent loading into the electrochemical system used to initiate the metal/soil interface is rarely discussed in literature.

### 1.1. Metal/soil interfacial structure

The interface which forms when soil comes in contact with a metallic surface can be described by the phenomenology of a double layer. To a first approximation, the equivalent circuit for the double layer structure can be modelled by an  $R_p C_{dl}$  – parallel network, whereby  $R_p$  is the polarisation resistance and  $C_{dl}$  is the double layer capacitance. This  $R_p C_{dl}$  parallel arrangement in series with the soil resistance ( $R_\Omega$ ), conforming to a simple Randle's circuit, can then be used to describe the complete electrical structure at the interface and the bulk of the soil media as illustrated in Fig. 1a. However, soil is a lossy dielectric which can be modelled by a resistor and capacitor in parallel ( $R_\Omega C$ ) as reflected in Fig. 1b. In fact some works related to corrosion studies in soil using the electrochemical impedance spectroscopy (EIS) method have reported the presence of two time constants [22,27] in the Nyquist plot. However, soil capacitance is rarely discussed in the context of electrochemical corrosion investigations.

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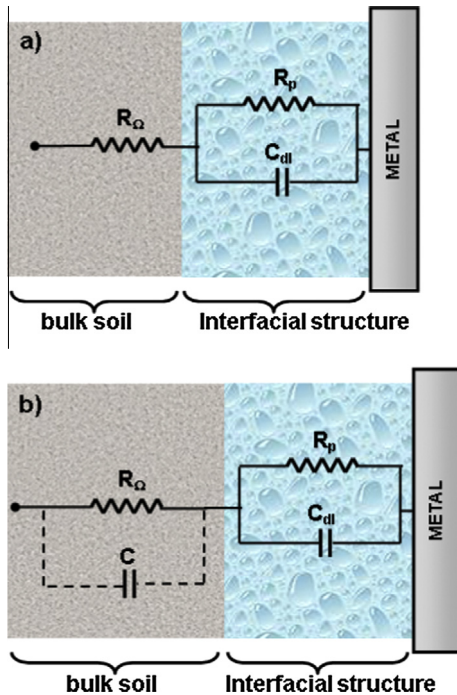


Fig. 1. Equivalent circuit diagram of the metal/soil interface and bulk soil with (a) negligible capacitive effect from soil, and (b) with the capacitive effect from soil.

The capacitance associated with soil will vary depending on the moisture content and clay content. The measured current during a potentiodynamic scan is composed of two components viz., the Faradaic current related to the corrosion process and the current resulting from the charging of the electrical double layer (EDL) at the metal/electrolyte interface. For soil, there will be a third current which would originate from the charging of the soil capacitance. Here, the choice of the scan rate [28] will be important since the magnitude of the capacitive current from soil will vary accordingly. This presents a difficult situation when analysing a large number of samples, since the optimal scan rate may vary amongst the different metal/soil electrochemical cells.

### 1.2. The galvanostatic pulse technique

Birbilis et al. [29] while studying steel corrosion in concrete recognised problems associated with LPR techniques in concrete/steel systems and the long times associated with EIS techniques. They identified a new approach to analysis of corrosion processes by using short ( $\leq 1$  s) galvanostatic pulses – a deviation from the longer pulses [30–33] usually applied to study concrete/steel corrosion systems; to acquire the charging and discharging curves along with curve-fitting techniques to extract the corrosion-related parameters, viz.,  $R_p$  and  $C_{dl}$ . This approach in essence bears some strategic similarity to analysing small overpotential potentiodynamic curves using the Butler–Volmer equation with curve-fitting techniques as suggested by Mansfeld [34,35]. In their work, Birbilis et al. [29] utilised the Kohlrausch–Williams–Watts formalism to model the charging/discharging curves as exhibiting a stretched exponential behaviour, arising due to the non-ideal behaviour of the  $C_{dl}$ . Their charging and discharging curves were modelled by a Randle's type circuit shown in Fig. 2a. They showed that given the applied current density is small ( $< 100 \mu\text{C cm}^{-2}$ ), significant resistances due to diffusion effects ( $R_D$ ) can be avoided and the potential-time response for the charging and discharging sections (illustrated in Fig. 2b) can be described by Eqs. (1) and (2) respectively.

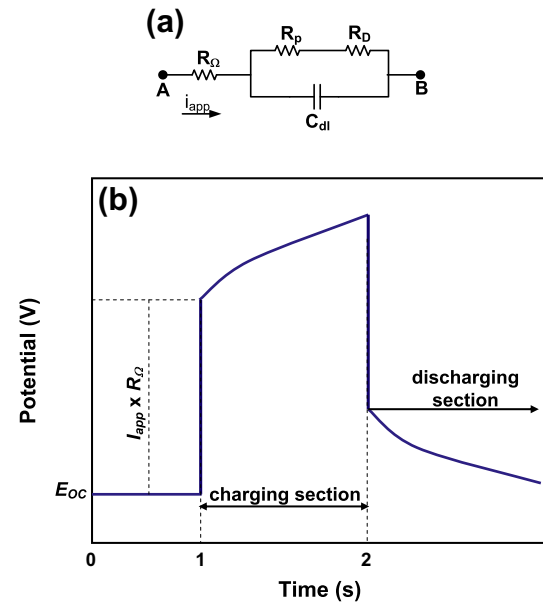


Fig. 2. (a) The Randle's type circuit used to model the interfacial response in concrete/steel systems, where  $R_D$  is the resistance that manifests due to significant diffusion effects [44], and (b) schematic of the charging and discharging sections on the potential-time response after application of a short (1 s) galvanostatic pulse across AB.

$$E(t) = i_{app}R_{\Omega} + i_{app}R_p \left( 1 - \exp \left( - \left[ \frac{t}{R_p C_{dl}} \right]^{\beta} \right) \right), \quad (1)$$

$$E(t) = i_{app}R_p \left( \exp \left( - \left[ \frac{t}{R_p C_{dl}} \right]^{\beta} \right) \right), \quad (2)$$

where  $E(t)$  is the potential-time response (V),  $i_{app}$  is the applied current (A),  $\beta$  is the stretched exponential factor (dimensionless), where  $0 < \beta \leq 1$ , and  $R_{\Omega}$  is the Ohmic resistance due to the electrolyte ( $\Omega$ ). The term  $i_{app}R_{\Omega}$  in Eq. (1) describes the instantaneous jump of the response curve corresponding to the instantaneous on-set of the charging process [36,37]. Regarding the discharging response however, some further scaling may be required to correct for possible partial charging of the interfacial double layer capacitance and thus non-steady state conditions. This can be achieved via Eq. (3).

$$E(t) = \gamma * \left[ i_{app}R_p \left( \exp \left( - \left[ \frac{t}{R_p C_{dl}} \right]^{\beta} \right) \right) \right], \quad (3)$$

where  $\gamma$  is a dimensionless parameter limited between  $0 \leq \gamma \leq 1$ . It is believed that the use of galvanostatic pulse techniques for measuring corrosion rates in soil or for the purpose of assessing soil aggressivity has never been conducted before in laboratory or in field. This is interesting since the technique possesses favourable characteristics to avoid the common difficulties usually encountered for practical measurements in resistive and inhomogeneous media [38].

The present laboratory study aims to investigate the use of galvanostatic pulse technique for measuring corrosion in soils, with a view to provide a framework for assessing aggressiveness amongst laboratory soil samples. A further scope of the present study is to evaluate and capture the effect of clay and chloride content on soil corrosivity.

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