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Decoupling pipeline influences in soil resistivity measurements with finite element techniques

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ABSTRACT

Periodic inspection of pipeline conditions is an important asset management strategy conducted by water and sewer utilities for efficient and economical operations of their assets in field. The Level 1 pipeline condition assessment involving resistivity profiling along the pipeline right-of-way is a common technique for delineating pipe sections that might be installed in highly corrosive soil environment. However, the technique can suffer from significant perturbations arising from the buried pipe itself, resulting in errors in native soil characterisation. To address this problem, a finite element model was developed to investigate the degree to which pipes of different a) diameters, b) burial depths, and c) surface conditions (bare or coated) can influence in-situ soil resistivity measurements using Wenner methods. It was found that the greatest errors can arise when conducting measurements over a bare pipe with the array aligned parallel to the pipe. Depending upon the pipe surface conditions, in-situ resistivity measurements can either be underestimated or overestimated from true soil resistivities. Following results based on simulations and decoupling equations, a guiding framework for removing pipe influences in soil resistivity measurements were developed that can be easily used to perform corrections on measurements. The equations require simple a-prior information on the pipe diameter, burial depth, surface condition, and the array length and orientation used. Findings from this study have immediate application and is envisaged to be useful for critical civil infrastructure monitoring and assessment.

1. Introduction

Deterioration and subsequent failure of critical civil infrastructure such as buried pipelines due to corrosive soil environment is a significant issue affecting water and sewer utilities (Cole and Marney, 2012; Deo, 2013; Ferguson and Geehman, 2001; Doyle et al., 2003; Peterson and Melchers, 2016; Moore and Emerton, 2010). Most of these pipelines are either made of mild steel, cast iron, or ductile iron and the deterioration mechanism of these materials through corrosion are well known (Peterson and Melchers, 2016; Gupta and Gupta, 1979; Ismail and El-Shamy, 2009). To ensure minimisation of service disruption and economical operation, most utilities engage proactively in condition monitoring and assessments of critical pipes to address essential needs for pipe renewals, repairs, or new construction.

Pipeline condition assessments are normally carried out at two different levels. Level 1 assessment is a general screening study, aimed at delineating sections of the pipe network that might be at higher risk of failure. Once these sections are identified, Level 2 assessment is then carried out to provide a detailed analysis of the pipe condition over the section. As part of Level 2 assessment, the pipes are usually excavated to reveal and characterise the extent of deterioration. In this manner, accurate localisation and identification of pipe sections with high probability of failure is very much dependent on the Level 1 assessment. A common methodology utilised in Level 1 assessment is the measurement of soil resistivities, at depths near to the pipe crown depth, along the pipeline right-of-way (ROW). The resulting spatial resistivity variations are then used for identifying potentially corrosive soils (Deo, 2013; Deo and Cull, 2015). Fig. 1 demonstrates a generally accepted qualitative analysis, whereby the soil resistivity profile along the pipeline ROW are used for identifying the locations and lengths of pipe sections at various corrosion severity levels in the native soil environment. The resistivity scale utilised here is from (Roberge, 2007), which clusters soil resistivities with level of corrosion severity as follows; 50–100 Ω m: moderately corrosive, 30–50 Ω m: corrosive, 10–30 Ω m: highly corrosive, and < 10 Ω m: extremely corrosive. Acquisition of resistivity variations in-situ, such as in Fig. 1, can be performed using various geoelectrical arrays (Reynolds, 2011). However, the Wenner 4-electrode array (hereafter referred to as the Wenner array/technique) (Reynolds, 2011; Telford et al., 1990) is considered in this work due to its simplicity and ease of use in the field, and is covered by the ASTM (ASTM G-57-95a, 2001) standard.

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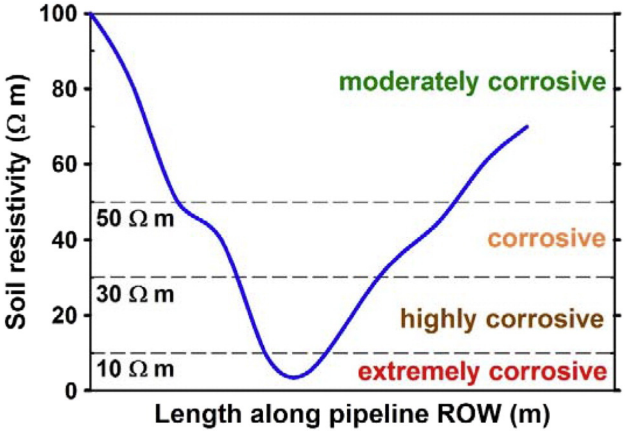

Fig. 1. Location and length of pipe sections exposed to different levels of corrosion severity based on soil resistivity profile along the pipeline ROW is an important Level 1 assessment. Various soil resistivities can be clustered into different corrosion severity levels as discussed in the paper.

1.1. Background on Wenner technique

The Wenner array consists of 4 collinear galvanic electrodes inserted in the ground usually to depths of ~4 cm. Current is injected via two current-electrodes, AB, and the potential difference on the surface is measured across a pair of potential-electrodes, MN, as illustrated in Fig. 2. The applied current can be either alternating current (AC), or direct current (DC) giving rise to different interpretation forms (Telford et al., 1990). However, for simple resistivity measurements DC conditions are used and the present study is based on this basis. Derivations of the resistivity expression based on this technique is well known (Telford et al., 1990; Everett, 2013). Instead it is noted that a current, I (A), injected via electrodes AB results in a potential difference, ΔU (V), measured between electrodes MN. This stimulus-response can be used to determine the apparent resistivity ρ_a (Ω m) using Eq. (1).

$$\rho_a = \frac{\Delta U}{I} \cdot 2\pi a, \tag{1}$$

where, a (m) is the electrode spacing as illustrated in Fig. 2. The term apparent resistivity is used to indicate measurements in an inhomogeneous half-space since it will vary depending upon the geometrical arrangement of the electrodes on the surface. In homogeneous conditions, the apparent resistivity corresponds to the true resistivity (ρ) of the half-space medium.

Resistivity profiling using Wenner techniques utilises a fixed electrode spacing, called a-spacing, to map lateral variations in soil resistivities. The entire array is advanced along a profile after measurements have been conducted at one station. The exact station location for the measurement corresponds to the centre of the 4-electrode arrangement and at a depth that is defined as follows. The depth of investigation (DOI) is the depth at which a thin horizontal layer parallel to the ground surface contributes the maximum amount of total measured signal at the ground surface (Evjen, 1938). Following the works of (Roy and Apparao, 1971; Roy, 1972; Edwards, 1977), the DOI for a Wenner array is computed as 0.173L, where L is the separation distance between A and B electrodes and is equivalent to 3a.

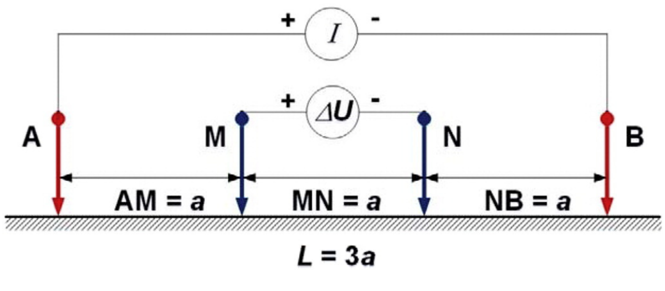

Fig. 2. The Wenner 4-electrode array of length L consisting of the current electrodes at A and B, and the potential electrodes at M and N. Note that the total electrode length $L = 3a$.

1.2. Application in pipeline condition assessments

A major concern regarding the use of the Wenner technique for subsurface soil resistivity characterisation as part of Level 1 pipeline assessment is the presence of the pipe itself. Electrical geophysical methods, including the Wenner technique, were initially developed for mineral exploration and in areas absent from major noise sources (Deo and Cull, 2016). In the context of assessing soil resistivities along pipeline ROW, the pipe behaves as a source of noise affecting the measurements. As a norm, they are avoided in conventional in-situ resistivity profiling. In their presence, survey lines are usually oriented perpendicular to the buried structures and this is addressed in the ASTM (ASTM G-57-95a, 2001) standard, where it is suggested that conductive pipelines should not be within a/2 length of the Wenner array, unless both are perpendicular to each other. For engineering assessment of soil corrosivity along the pipeline ROW, it is obvious that a shift in the conventional data collection procedure is required. This is because pipelines constitute the important element in the measurement objective. Usually, limited information is available on the manner in which resistivity profiling along pipeline ROW using Wenner technique is conducted in practice. This is especially in regard to the array configuration (electrode spacing) and orientation (parallel or perpendicular), and whether the measurements are influenced by the pipeline, which may be either bare (conducting), or coated (insulating). Since these measurements constitute important economical level decisions, it is essential that accurate scientific information is provided.

An important work in literature concerning the effects of pipe and their removal from apparent resistivity measurements is by (Vickery and Hobbs, 2002). They investigated pipe diameter, depth, and orientation influences on measurements and provided a method for their detrending in order to enable interpretation of underlying geology. Their method used the analytical solution to the Laplace equation for the potential at a given location in a homogeneous half-space consisting of a buried cable formulated by (Wait, 1982). However, they did not indicate the degree of influence exerted by insulated pipes on the measurements. The formulations by (Wait, 1982) provide analytical expressions for the primary potential, which is due to a current source, and the secondary potential that will arise due to the conductive pipe. The calculation of the primary potential is straightforward, while solving for the secondary potential requires numerical integration of a modified Bessel function of the second kind (Vickery and Hobbs, 2002). The total potential at a location is then a superposition of the primary and secondary potentials due to the two current sources. An inherent condition imposed on the secondary potential expression by (Wait, 1982) is that the cable radius is very small, i.e., it acts as a source of filament line current.

In view of the use of resistivity profiling methods in pipeline condition assessments, a practical framework is warranted that provides guidance on the use of Wenner technique in Level 1 assessments for accurate quantification of native soil resistivities. The accuracy here involves being able to remove pipe influences from the entity of interest. To avoid the tedious computations necessary for the analytical expressions case by case for all possible dimensionality of the pipe in soil, a general correction method is necessary that is expressible in terms of readily available information. With this conviction, the present work was aimed at identifying the limitations and providing robust correction procedures necessary for in-situ soil resistivity measurements. This was achieved with the development of a 3D finite element model to better understand the influence of pipe diameters, burial depths,