Journal of Applied Geophysics 127 (2016) 45–55

Contents lists available at ScienceDirect

Journal of Applied Geophysics

journal homepage: www.elsevier.com/locate/jappgeo

How should an electrical resistivity tomography laboratory test cell be designed? Numerical investigation of error on electrical resistivity measurement

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ARTICLE INFO

Article history:
Received 4 April 2015
Received in revised form 28 January 2016
Accepted 17 February 2016
Available online 18 February 2016

Keywords:
Electrical resistivity tomography
Laboratory
3D complete forward modelling

ABSTRACT

Among geophysical methods, the electrical resistivity tomography (ERT) method is one of the most commonly used for the study of hydrodynamical processes. The geophysical literature relates several laboratory-scale applications of this method. Unlike the measurements taken at the field scale, few authors have taken an interest in errors associated with apparent electrical resistivity, especially in the case of ERT data acquired in the laboratory. The objective of this paper is to show that laboratory errors related to the positioning of electrodes and the geometry of cells are significant on apparent resistivity measurements. The embedment and the position of the electrode were evaluated to quantify their impact on electrical resistivity measurement. To assess these impacts, the authors propose a 3D numerical modelling investigation based on the complete design of a laboratory test cell.

1. Introduction

Electrical resistivity tomography (ERT) is a mature geophysical method that is increasingly popular in environmental and hydrogeological studies (Barker, 1998; Binley and Kemna, 2005; Chambers et al., 2013; Loke, 2004; Loke et al., 2013; Ogilvy et al., 2002). This near-surface geophysical method provides information in various field applications: (i) for geological purposes, Van Schoor (2002) used ERT for sinkhole detection and bedrock and sand channel localization; (ii) in a hydrogeological study, Descloitres et al. evaluated the location of shallow and deep infiltrations and recharge zones with time-lapse monitoring (Descloitres et al., 2008); (iii) to monitor pollution plumes Benson (1995); Benson et al. (1997) mapped the extent of plume pollution in soil; (iv) in a municipal solid waste landfill, the leachate flow which is a key point in controlling anaerobic waste biodegradation, the ERT method was used to highlight the volume of waste mass impacted during leachate recirculation events (Audebert et al., 2014; Clement et al., 2009; Clément et al., 2009; Moreau et al., 2003).

This list illustrates the various applications of the ERT method related to its many advantages: (i) it is non-destructive: the hydromechanical properties of the subsurface or hydrodynamic processes can be evaluated without digging; (ii) it is sensitive to the contrast in conductivity between the solid and liquid phases of the medium studied and (iii) it may indicate the distribution of electrical resistivity in 2D or 3D with the recent development of inversion software (Loke et al., 2013). Despite all of the advantages of the ERT method, interpretations of the electrical resistivity variations are not always obvious because the electrical resistivity can be influenced by several parameters; the most frequently cited are: water content, temperature, porosity, density and electrical conductivity of the liquid phase, (Archie, 1942; Benderitter, 1999; Clement et al., 2011; Day-Lewis et al., 2003; Moreau et al., 2011; Rhoades and Van Schilfgaarde, 1976; Salem and Chilingarian, 1999). Even if the method was developed for field applications, a great deal of research has been conducted at the laboratory scale to study one of the parameters involved in the process studied under control conditions (Brunet et al., 2011; Han et al., 2015; Kowalczyk et al., 2014; Rhoades and Van Schilfgaarde, 1976). (i) Brunet et al. (2011) have calibrated the relationship between electrical resistivity and the soil's water content to estimate water deficit at the field scale. (ii) To explain the ranges of resistivity variation observed during leachate reinjection surveys in a municipal solid waste landfill, Moreau et al. (Moreau et al., 2011) conducted a series of laboratory tests on waste samples to relate variations in density and moisture content to the electrical resistivity recorded. The authors proposed a methodology to estimate interpreted resistivity anisotropy between vertical and horizontal resistivity measurements at the laboratory scale. (iii) In another experiment, Slater et al. (2000) used a high-resolution 3D electrical resistivity tomography with cross-borehole arrays to study solute transport in a large experimental tank. The authors conducted a salt tracer experiment, monitored by time-lapse ERT, in a quasi-two-dimensional sandbox with the aim of determining the hydraulic conductivity distribution in the domain. They

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http://dx.doi.org/10.1016/j.jappgeo.2016.02.008
0926-9851/

concluded that temporal moments of potential perturbations obtained during salt tracer tests provide a good basis for inferring the hydraulic conductivity distribution by fully coupled hydro-geophysical inversions. (iv) Binley et al. (1996) used ERT to study the internal spatial characteristics of solute transport in naturally heterogeneous soils: the analysis of the results revealed spatial variation in transport characteristics throughout the soil column.

Most of the volume of the experimental cells is less than 1 m^3 (Brunet et al., 2011; Moreau et al., 2011; Slater et al., 2002) and the question addressed by many authors is the position and the spacing between the electrodes to describe the entire medium studied (Moreau et al., 2011). For all the approaches presented above, two types of analysis were always encountered. The first ones consider that the distribution of resistivity is homogeneous and that apparent electrical resistivity can be considered as interpreted resistivity, as in older studies (Archie, 1942; Jackson, 1978; Kowalczyk et al., 2014; Liu et al., 2013; Rhoades and Van Schilfgaarde, 1976). The second type of analysis does not retain the same assumption and requires inversion software to calculate the interpreted resistivity distribution in the medium studied from the measured apparent resistivity (Clement and Moreau, 2012; Slater et al., 2002). In both cases, a geometric factor related to the electrodes' location is required to calculate apparent electrical resistivity. Experimental tests with solutions of known electrical conductivity are possible (as proposed by Rhoades et al. (1976)) and numerical simulation software is available to provide this evaluation. When a forward modelling algorithm is used to evaluate the geometric factor, the position, size and shape of the electrodes have to be known with the highest accuracy. However, a great deal of additional information is needed: the shape and size of the test cell must be measured and the embedment of the electrodes in the medium studied must be identified. The numerous numerical tools available now following the technical development of computers and computer languages can provide a full and accurate description of the experimental conditions. For the second type of analysis using inversion processes, electrode shape, size and embedment are difficult to take into account in the inversion software available, such as BERT (Boundless Electrical Resistivity Tomography), developed by Günther et al. (2006), or R3T, defined in Binley and Kemna (2005). Generally, the electrodes are described as a point electrode in the laboratory test cell designed in the inversion software.

One of the key parameters is the position of the electrode represented by point node because even if the theoretical position of the point node is perfectly defined during the design of the laboratory test cell, in fact, there is always an error associated with the mechanical construction of the laboratory test cell. The position and the error on that position have an impact on the calculation of the geometric factor of the quadripole because the characteristics of the complete electrode cannot be ignored when spacing is short in laboratory tests.

This paper proposes guidelines to design an example of a cylindrical laboratory test cell for ERT measurements using a numerical approach. The influence of electrode size and impact of the error on its position and its embedment are studied to define the accuracy needed to guarantee the computation of apparent resistivity and indirectly the distribution of interpreted resistivity using inversion software.

2. Material and methods

In ERT laboratory measurements, several parameters can create errors on the apparent resistivity calculation and the evaluation of interpreted resistivity using inversion software. Considering that the instruments used for current injection and potential measurements are calibrated, we identify three major errors which could influence the geometric factor associated with a quadripole: (i) the electrode shape and size, (ii) the accurate measurement of electrode embedment and (iii) the accurate measurement of the electrode position. To estimate the impact of these parameters on the geometrical factor, we chose a classical numerical methodology based on multiple numerical forward modelling currently applied in geophysics (Clement et al., 2009; Clément et al., 2010; Radulescu et al., 2007; Yang, 2005). We chose to base our modelling approach on our experimental laboratory test cell (LTC) presented in Fig. 1a.

For all numerical modelling, the first step is the design of the LTC for different conditions: shape, size, embedment and electrode position. The second step is the calculation of the geometric factor for each combination of conditions imagined and the last one is the evaluation of the distribution of the results according to the parameters tested.

2.1. Laboratory test cell description for numerical design

During the last 5 years, we conducted laboratory tests on waste samples to study relations between the electrical resistivity variations observed and different hydro-mechanical conditions such as density and water content (Moreau et al., 2011). Our experimental test cells always had the same cylindrical shape and an average volume of 0.226 m^3 for 1 m height and 0.4 m diameter. These configurations were considered to design the LTC for the different numerical models tested in this paper. The LTC is made of high-density polyethylene (HDPE). Forty steel electrodes are distributed over five levels and eight vertical lines spaced 45° apart. Fig. 1a–b describes the theoretical shape, embedment and positions of the electrodes. The conventional electrodes used are cylindrical and exceed 30 mm inside the test cell. They are spaced vertically 150 mm apart and 157 mm apart horizontally on the perimeter of the test cell.

2.2. Electrical resistivity measurement

The ERT method is thoroughly described in the geophysical literature (Chapellier, 2000; Dahlin, 2001; Loke et al., 2013). The apparent resistivity ρ_{app} is calculated from a quadripole composed of two injected current electrodes A and B and two other electrodes M and N to measure a potential difference (Eq. 1). The geometric factor k depends on the position of the four electrodes called quadripole as well as the size and the shape of the electrodes when they cannot be considered to be a point in the measurement process.

$$\rho_{app} = \frac{k \times \Delta V_{MN}}{I_{AB}} \tag{1}$$

where:

ρ_{app}	is apparent electrical resistivity ($\Omega \cdot m$)
ΔV_{MN}	is the electrical potential difference measured (V)
I	is the intensity of the injected current (A)
k	is the geometric factor (m).

The electrical resistivity arrays evaluated are the Wenner-α and the dipole–dipole array because they are the most popular (Fig. 2). From the top of the test cell, the electrodes are numbered from 1 to 40: the first level considers electrodes 1–8 and the lowest level electrodes 33–40. The vertical distance between two consecutive electrodes is equal to 150 mm, the position of the top and the bottom are, respectively, 175 mm from the upper level of the electrodes (1–8) and 125 mm from the lowest level of the electrodes (33–40).

Among all imaginable quadripoles from the 40 electrodes implemented, four quadripoles were selected as being the most frequently used. The first quadripole Q1, called the horizontal, consists of four electrodes located on the same level and spaced 45° apart (Fig. 2). The second, Q2, is the vertical and considers the four electrodes on the same vertical line. The third, Q3, is the diagonal; four consecutive electrodes are all placed at different levels. The last array, Q4, is a mixed array between all of these positions. Two consecutive electrodes are at the same level and two others are also at the same level but different from the previous and on the opposite side of the LTC.