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A general approach for DC apparent resistivity evaluation on arbitrarily shaped 3D structures

Laurent Marescot [a,b,*], Stéphane Rigobert [c], Sérgio Palma Lopes [a], Richard Lagabrielle [a], Dominique Chapellier [b]

[a] Laboratoire Central des Ponts et Chaussées, 44341 Bouguenais, France
[b] Institute of Geophysics, University of Lausanne, 1015 Lausanne, Switzerland
[c] Laboratoire Central des Ponts et Chaussées, 75732 Paris, France

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Abstract

This paper presents a general and comprehensive way to evaluate the geometric factors used for the computation of apparent resistivities in the context of DC resistivity mapping and non-destructive investigations, in laboratory or in the field. This technique enables one to consider 3-dimensional objects with arbitrary shape. The expression of the geometric factor results from the early definition of apparent resistivitiy. It is expressed as the ratio of the resistances obtained from measurements to the resistances induced in the medium with unitary resistivity considering the same object geometry and electrode set-up. In this work, a finite element code is used for the computation of the geometric factor. In this code, the electrodes do not need to be located on the nodes of the mesh. This option makes the finite element mesh generation task easier. A first synthetical example illustrates how the present approach could be applied to apparent resistivity mapping in an environment with a complex underground topography. A second example, based on real data in a water tank, illustrates the simulation of a resistivity survey on a structure with finite extent, e.g. a laboratory sample. In both examples, topographic artefacts and effects of material sample shapes are successfully taken into account and reliable apparent resistivity descriptions of the structures are obtained. The effectiveness of the method for the detection of heterogeneities in apparent resistivity maps is highlighted.

Keywords: Apparent resistivity; Geometric factor; Cell constant; Topography correction; Finite element modelling; Laboratory measurements

1. Introduction

Recent improvements in data acquisition combined with the development of powerful computer workstations have encouraged the use of resistivity techniques for non-conventional problems. Resistivity methods are of great interest in civil or mining engineering investigations to examine the structure of tunnels, underground quarry columns or mine galleries, as a helping tool for the planning of safe gallery extensions. In these applications, the terrains may have an uneven topography and a half-space approximation may not be applicable to the overall geometry of the problem (e.g. Sasaki and Matsuo, 1990; Dobroka et al., 1991; Draskovits and Simon, 1992; Hering et al., 1995; Maillol et al., 1999; Yaramanci, 2000; Yaramanci and Kiewer,

* Corresponding author. Currently: Institute of Geophysics, ETH-Swiss Federal Institute of Technology, HPP O7 ETH Hoenggerberg, CH-8093 Zurich, Switzerland. Tel.: + 41 44 633 75 61; fax: +41 44 633 10 65.

E-mail address: laurent@aug.ig.erdw.ethz.ch (L. Marescot).

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2000). In non-destructive investigations and petrophysical analysis, the electrical properties of material samples (e.g. soil, rock or concrete core samples) or architectural ornamentations (Lataste, 2002; Taylor and Barker, 2002; Giao et al., 2003) are studied. Electrical techniques are also used in medical and biological engineering to study the structures and properties of human body (Lionheart, 2004) or biological samples from a set of measurements made around, sometimes inside, the investigated object (Faes et al., 1999; Linderholm et al., 2004). In these examples, the domain investigated has a finite extent (e.g. a laboratory test-cell) and a complex shape or topography.

Resistivity methods are employed on complicated 3-dimensional (3-D) models and a large number of parameters is required to describe the geometry accurately. Measured apparent resistivity data need to be inverted using an iterative algorithm to give a clearer image of the investigated structures. Nevertheless, there are still some fields of interest where apparent resistivities are directly used to infer information on the properties of an object, like for laboratory petrophysical measurements (e.g. Lataste, 2002; Taylor and Barker, 2002; Giao et al., 2003), or at a larger scale in resistivity mapping or profiling (e.g. VanGemert et al., 1996; Marescot et al., 2003a) or in well-logging and for borehole measurements (e.g. Le Masne and Poirmeur, 1988; Poirmeur and Vasseur, 1988; Leroux, 2000). Resistivity mapping techniques currently meet new expectations with the developments of mobile galvanic or electrostatic arrays (Panissod et al., 1997). Apparent resistivities are also used in processing electrical anisotropy for fracture and karst detection or petrophysical determination (Watson and Barker, 1999; Busby, 2000) or in monitoring of complex structures like volcanoes (Utada, 2003).

Apparent resistivity rather than electrical resistance is used by geophysicists and engineers when investigating the electrical properties of an object. By relating the electrical resistance to the array dimension, each measurement will depend more on the electric structure of the object than on the array length. The electrical resistance values are traditionally transformed into apparent resistivity values using the geometric factor of each array, which can be calculated only for simple geometric models, such as a half space or a cylindrical sample. Since the global electrical measurements are influenced by the outline of the sample, this frequently implies to reshape the object or to apply some crude approximations, which are not always satisfactory solutions. There is therefore a need in having a totally versatile technique to evaluate apparent resistivities in any situation and especially for the cases outlined above. When the investigated object features an arbitrary shape, however well known, the determination of apparent resistivity can be carried out, referring to the most general definition of apparent resistivity as recalled here after.

In this paper, a procedure is presented for an easy and reliable computation of the apparent resistivity parameter on any 2-D or 3-D structure of arbitrary shape, in the laboratory or in the field, and using any electrode layout. The apparent resistivity formulation is first detailed. The following section concerns an application of the method to the apparent resistivity mapping of a synthetic model with strong underground topography. Finally, laboratory tank measurements are presented to illustrate the effectiveness of the method for petrophysical characterization and resistivity mapping.

2. Approaches to defining apparent resistivities

2.1. Analytical approach

The potential values are traditionally (Kunetz, 1966) transformed into apparent resistivities by multiplying the measured resistance by the array geometric factor. The following relation is generally used, with G the geometric factor, expressed in meters, and R the electrical resistance, expressed in ohms:

$$\rho_{\text{app}} = GR \tag{1}$$

with

$$G = \frac{4\pi}{\frac{1}{AM} - \frac{1}{AN} - \frac{1}{BM} + \frac{1}{BN} - \frac{1}{A'M} - \frac{1}{A'N} - \frac{1}{B'M} + \frac{1}{B'N}} \tag{2}$$

where A and B are the current electrodes and M and N the potential electrodes. A' and B' are the images of A and B with respect to the ground surface (see Fig. 1). It has to be emphasized that this expression for G is only strictly correct for a flat earth.

This user friendly expression of G (Eq. (2)) originates from the early geoelectrical prospecting schemes. It is very popular and has become sort of a standard used by most geophysicists. Nevertheless, direct current resistivity methods are now applied to a wide variety of fields where the flat earth model is clearly not the standard reference anymore. As a conventional choice, Eq. (2) could still be used, but it is a well known fact that it brings strong artefacts in the case of a more arbitrary geometry or topography (e.g. resistivity mapping along a cliff, a canyon or in a tunnel). Therefore, a more