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Tomographic inversion of time-domain resistivity and chargeability data for the investigation of landfills using a priori information

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A B S T R A C T

In this paper, we present a new code for the modelling and inversion of resistivity and chargeability data using a priori information to improve the accuracy of the reconstructed model for landfill. When a priori information is available in the study area, we can insert them by means of inequality constraints on the whole model or on a single layer or assigning weighting factors for enhancing anomalies elongated in the horizontal or vertical directions. However, when we have to face a multilayered scenario with numerous resistive to conductive transitions (the case of controlled landfills), the effective thickness of the layers can be biased. The presented code includes a model-tuning scheme, which is applied after the inversion of field data, where the inversion of the synthetic data is performed based on an initial guess, and the absolute difference between the field and synthetic inverted models is minimized.

The reliability of the proposed approach has been supported in two real-world examples; we were able to identify an unauthorized landfill and to reconstruct the geometrical and physical layout of an old waste dump. The combined analysis of the resistivity and chargeability (normalised) models help us to remove ambiguity due to the presence of the waste mass. Nevertheless, the presence of certain layers can remain hidden without using a priori information, as demonstrated by a comparison of the constrained inversion with a standard inversion. The robustness of the above-cited method (using a priori information in combination with model tuning) has been validated with the cross-section from the construction plans, where the reconstructed model is in agreement with the original design.

1. Introduction

The detection and imaging of landfills are challenging tasks in geophysics, not only because of the required resolution and depth of penetration but also because major pitfalls may arise in such complex areas from the speculative interpretation of geophysical anomalies as geological or anthropogenic features (De Carlo et al., 2013). In particular, the latest national regulations (D.Lgs. 36/2003) were not everywhere adopted for the now covered landfill in Italy before 2003 and it could be difficult to reconstruct the effective succession of layers. Many landfills need prospecting for site management to assess the effective thickness of the different layers (e.g., compacted clay and saturated waste mass) and to verify the groundwater contamination due to leachate flow outside the landfill. In this sense, geophysical surveys can fulfil this target as long as they are able to investigate the whole landfill as constituted by anthropogenic (e.g., waste mass and leachate) and geological (e.g., clay and water table) features (Cardarelli and Bernabini, 1997). We can reconstruct the effective layering of the landfill to verify a possible leachate flow outside the site using geoelectrical methods, investigating both the resistive and the capacitive response of the waste mass (Gazoty et al., 2012). In fact, the waste layer is primarily depicted with a relatively high chargeable (>10 mV/V) and conductive (<2 Ω m) unit with respect to the surrounding media.

Electrical resistivity tomography (ERT) has been used worldwide for contaminant detection (e.g., Benson et al., 1997; Dahlin et al., 2002), investigation of landfills (e.g., Ogilvy et al., 2002; Cardarelli and Di Filippo, 2004; Chambers et al., 2006), and monitoring leachate injection (e.g., Audebert et al., 2016; Clément et al., 2010, 2011; Grellier et al., 2008) or DNAPLs source zones (e.g., Chambers et al., 2010; Power et al., 2014). ERT has also been employed in combination with induced polarisation (IP) methods, where the acquisition is often performed in the time-domain for site monitoring (e.g., Ustra et al., 2012), monitoring of the DNAPLs plume (e.g., Cardarelli and Di Filippo, 2009), and classification of the contamination level (Turai, 2011). The added valued given by the joint analysis of the resistive and capacitive response of the subsoil has been demonstrated during last decades (e.g.,

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Martinho and Almeida, 2006; Dahlin et al., 2010; Gazoty et al., 2012). In fact, the IP method is particularly sensitive to changes related to the presence of waste disposal or contamination (electrochemical polarisation), as well as changes in the clay content of geological formations (membrane polarisation).

The 2D and 3D inversions of ERT and IP datasets were frequently performed in literature by commercial software, such as RES2DINV/RES3DINV (Loke and Barker, 1996) or ERTLab (Geostudi Astier and Multiphase Technologies). Although these codes are rapid and reliable, they are closed-source programs, and the user cannot control the entire workflow or add new functions. Alternatively, open-source algorithms already available worldwide, such as BERT (Günther et al., 2006), RESINVM3D (Pidlisecky et al., 2007), or EIDORS (Adler and Lionheart, 2006), perform almost only the inversion of ERT data, even though Karaoulis et al. (2013) recently developed a software in Matlab to perform ERT and IP inversion (IP4DI). In particular, EIDORS is a Matlab-based open-source software that was firstly developed for medical applications with the aim to share data and promote collaboration between groups working in this field. EIDORS is a well-known package for electrical impedance tomography, generally performing a resistivity inversion on 3D cylindrically shaped domains with a linearised procedure. However, this code cannot be used in its current form to work on prismatic domains using a wider range of parameters (always for geophysical surveys). Moreover, an inversion code should take into account information coming from boreholes, direct inspection, and construction plans in the case of landfills to validate the inversion results. In the following sections we present a numerical code developed within the EIDORS environment, which is able to solve the 2D forward and inverse problems both for resistivity and chargeability and to embed a priori information within the numerical routines.

In addition, the effective thickness of the layers can be biased when we have to face a multilayered scenario with numerous resistive to conductive transitions (the case of landfills) and using ERT in combination with IP may be not sufficient to completely remove ambiguities in the interpretation of the inverted models. Therefore, the speculative interpretation of the inverted models is generally not adequate when we need to know the geometrical and physical layout of the landfill with a sufficient accuracy, and actions to remove these ambiguities should be adopted.

The main goals of this work are as follows:

- to evaluate the benefit of a priori information for the characterisation of landfills with a comparison between the standard approaches, where inversion is performed using a new code;
- to present a method for the ambiguity removal in the interpretation of landfill models by means of a model-tuning routine;
- to discuss the above-cited procedures with applications to real-world examples from the investigation of landfills.

2. Materials and methods

2.1. Electrical parameters

The subsoil generally exhibits both a resistive and a capacitive response, where an external DC current source is turned on. The former effect can be modelled by means of the bulk resistivity (Archie, 1942):

$$\rho = \rho_w S^{-n} \Phi^{-m}, \tag{1}$$

where ρ_w is the solution resistivity, S is the degree of saturation, Φ is the porosity, and n and m are exponents depending on the tortuosity and cementation of the investigated medium.

The resistivity can be a diagnostic parameter for landfills because the high salinity of fluids often saturating the waste mass (leachate) usually makes them very conductive, in contrast to both the covering layer, often drier (Aristodemou and Thomas-Betts, 2000), and the bottom liner (HDPE) that acts as an insulator (resistivity of $10^7\,\Omega\,\text{m}$). However, if the waste mass is almost dry or inhomogeneous or if the clay constitutes a large fraction of the cover, it can be critical to distinguish the cover material from the waste (Ogilvy et al., 2002; Leroux et al., 2007). In addition, the identification of leaks is often unrealistic because the resistivity range of the clay bottom layer and the saturated waste are comparable (1–10 Ω m). To overcome these issues, we can also address the capacitive response of the subsurface in terms of chargeability, the ratio of the capacitive-to-conductive properties of the material at low frequencies (Slater and Lesmes, 2002). Chargeability is therefore linked to the changes in the bulk resistivity as it increases in the presence of a saline fluid (e.g., leachate), while no clear correlation is observed as a function of the clay content (Slater and Lesmes, 2002). Elsewhere in a landfill (covering, liners, dry waste), these parameters should be close to zero.

2.2. Code implementation

The theoretical formulation for solving the forward problem (Appendix A) and the inversion process (Appendix B) for resistivity and chargeability have been numerically implemented in Matlab using the VEMI algorithm—versatile algorithm for electrical modelling and inversion (De Donno and Cardarelli, 2015). This algorithm is capable to invert both time- and frequency-domain datasets acquired in the laboratory or in the field, and it is included in the open-source EIDORS environment. The choice of the piecewise path to be followed by the user is controlled in VEMI by the global variable *type* with four attributes: *domain* (time- or frequency-domain), *shape* (cylindrical for the laboratory or prismatic for the field survey, respectively), *geometry* (2D or 3D), and *inversion* (synthetic modelling or inversion), assuming values of 0/1 as a function of the particular choice. Each path is associated with the related functions for solving the forward and inverse problems (Eqs. (A.1)–(A.4) for 2D resistivity and chargeability modelling and (B.1)–(B.5) for data inversion). Furthermore, versatile elements have been added to VEMI, which were specifically developed for landfills to reduce the degree of uncertainty in interpreting the geophysical models.

2.3. Versatile elements for landfills

2.3.1. Use of a priori information

When a priori information is available in the study area (e.g., we know length and thickness of the landfill layers), we can insert it in VEMI using inequality constraints on the new model vector $\mathbf{m}'$ (Kim et al., 1999):

$$\mathbf{m}' = \ln\left(\frac{\mathbf{m} - \mathbf{a}}{\mathbf{b} - \mathbf{m}}\right), \tag{2}$$

where $\mathbf{a}$ and $\mathbf{b}$ are vectors containing minimum and maximum acceptable values for the study parameter. This procedure can be applied both for the chargeability and resistivity model vectors, only within a particular sub-domain (e.g., the waste mass), or in the whole domain.

If information about the preferential direction of the anomalies is available, we can insert it by adding weights to the smoothness matrix in Eq. (B.3), as:

$$\mathbf{L} = \alpha_x \mathbf{L_x} + \alpha_z \mathbf{L_z}, \tag{3}$$

where α_x and α_z are the weighting factors to enhance the anomalies elongated in the *x*- or *z*-directions. For a layered medium, $\alpha_z < \alpha_x$;

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