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3D electrical resistivity tomography of karstified formations using cross-line measurements

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ABSTRACT

The acquisition of a full 3D survey on a large area of investigation is difficult, and from a practitioner's point of view, very costly. In high-resolution 3D surveys, the number of electrodes increases rapidly and the total number of electrode combinations becomes very large. In this paper, we propose an innovative 3D acquisition procedure based on the roll-along technique. It makes use of 2D parallel lines with additional cross-line measurements. However, in order to increase the number of directions represented in the data, we propose to use cross-line measurements in several directions. Those cross-line measurements are based on dipole-dipole configurations as commonly used in cross-borehole surveys. We illustrate the method by investigating the subsurface geometry in a karstic environment for a future wind turbine project. We first test our methodology with a numerical benchmark using a synthetic model. Then, we validate it through a field case application to image the 3D geometry of karst features and the top of unaltered bedrock in limestone formations. We analyze the importance of cross-line measuring and analyze their capability for accurate subsurface imaging. The comparison with standard parallel 2D surveys clearly highlighted the added value of the cross-lines measurements to detect those structures. It provides crucial insight in subsurface geometry for the positioning of the future wind turbine foundation. The developed method can provide a useful tool in the design of 3D ERT survey to optimize the amount of information collected within a limited time frame.

1. Introduction

In the last two decades, electrical resistivity tomography (ERT) has been widely applied in many different contexts such as groundwater resources (e.g., Hermans et al., 2015; Yeh et al., 2015), fault imaging (e.g., Nguyen et al., 2005; Suski et al., 2010) and geotechnical applications (e.g., Chambers et al., 2013; Sauret et al., 2015). The wide range of applications of ERT is a result of the large number of parameters influencing the electrical resistivity of the subsurface (porosity, fractures, rock/soil type, saturation, temperature, fluid electrical conductivity, etc.) and the robustness of the method. Because of the simplicity of field implementation, requiring only one to two people for a couple of hours, 2D surveys are not time-consuming and relatively cost-effective. In addition, acquisition times have drastically decreased with the advent of multi-channel systems and automated switching systems (LaBrecque et al., 1996). Nevertheless, one of the major drawbacks of 2D surveys is the underlying assumption that the subsurface is actually 2.5D, i.e. that electrical resistivity is constant in the direction perpendicular to the profile. This assumption allows reducing the complexity of forward modeling from 3D to 2D using a Fourier-cosine transformation (Dey and Morrison, 1979). Most interpretation software, commercial or academic, uses this assumption in the inversion of 2D data sets.

The 2.5D assumption can be valid for certain conditions (profile perpendicular to main geological structures, relatively homogeneous subsurface), but it can also lead to distorted and misleading results in strongly variable and heterogeneous environments (e.g. Bentley and Gharibi, 2004; Nimmer et al., 2008), such as encountered in karstic settings. In such cases or when a detailed mapping of the subsurface is required, 3D acquisition and inversion techniques must be considered. This remark is particularly true for karstic hazard where the 3D nature of the dissolution processes makes the 2.5D hypothesis of the subsurface much weaker than for fault imaging for example.

In most cases, the acquisition of a full 3D survey on a large area of investigation is difficult and, from a practitioner's point of view, very costly. The number of electrodes increases rapidly, the time to acquire a complete data set and the required equipment are prohibitive. In most

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applications, 3D surveys with a substantial number of electrodes (>100) are not full 3D surveys but limited to the two main directions and the cross-diagonal (e.g., Oldenburg and Li, 1994; Kaufmann and Deceuster, 2007). Fiandaca et al. (2010) developed a 3D acquisition procedure called maximum yield grid which limits the number of pairs of electrode used for current injection and therefore reduces the impact on vulnerable surfaces such as archeological sites (Capizzi et al., 2012).

However, to limit logistic constraints and optimize the acquisition time, 3D surveys are generally designed as extensions of 2D surveys and can be performed with a limited amount of electrodes connected to the resistivity meter at a certain moment in time. The most common solution is then to deploy 2D parallel lines. The acquisition is 2D but the data are processed using a 3D inversion code which accounts for heterogeneity in the direction perpendicular to the 2D lines (e.g., Chambers et al., 2011; Orfanos and Apostolopoulos, 2011; Ustra et al., 2012). The extension in both directions depends on the objectives of the investigation. Rucker et al. (2009b) used 12 long lines of 140 electrodes with 3 m electrode spacing and 15 m line spacing, covering an area of about 70,000 m^2 to investigate a gold heap. In contrast, Papadopoulos et al. (2010) carried out a square survey of 26 lines of 26 electrodes with 1 m electrode- and line-spacing in tumuli investigations.

2D parallel surveys are relatively fast given the high number of electrodes generally used, but they suffer from the limited 2D acquisition. Indeed the sensitivity to resistivity changes in the perpendicular direction rapidly decreases for 2D surveys and most perpendicular structures might be poorly imaged. To overcome this limitation, many authors have proposed to use 2D lines in two orthogonal directions in order to acquire data in more than one direction (e.g., Bentley and Gharibi, 2004; Berge and Drahor, 2011; Negri et al., 2008) Those studies have shown that the inversion results of 2D orthogonal setups were more satisfactory, except if the direction of the anomaly was already known or the electrode interspacing was sufficiently small. For large domains, Rucker et al. (2009a) have shown that inverting the whole data set at once yielded better results than inversions on sub-domains.

To consider data collection in more than two directions, some authors have also proposed radial or star shaped surveys (e.g., Nyquist and Roth, 2005; Tsourlos et al., 2014), providing more information on the heterogeneity of the subsurface in the central part of the investigated zone non-standard 3D surveys, such as C-shape or L-shape (e.g., Chávez et al., 2014), square-shape (Argote-Espino et al., 2013) or ring-shape (Brunner et al., 1999) have also been tested in complex environments where it is not possible to use electrodes on a large area.

However, both orthogonal and radial surveys ask for additional field work by increasing the number of lines to acquire. Dahlin et al. (2002), in contrast, proposed a roll-along methodology in the orthogonal directions to acquire simultaneously 2D parallel lines and orthogonal measurements. They propose to set-up several parallel lines at the same time and to acquire cross-line measurements in the orthogonal direction using electrodes already connected on the parallel lines. When the first line has been acquired, it is removed and placed next to the last line as in classical roll-along. Dahlin et al. (2002) tested the procedure with a pole-pole survey on a 17 lines survey with 21 electrodes, using 6 cross-line measurements (7 cables) in the orthogonal direction. This procedure reduces significantly the time spent on the field but provides a data set less complete than a full orthogonal survey and still limits the number of measurement directions during data acquisition.

In this paper, we propose an innovative 3D acquisition procedure based on the roll-along technique of Dahlin et al. (2002). It makes use of 2D parallel lines with additional cross-line measurements. However, in order to increase the number of directions represented in the data, we propose to use cross-line measurements in several directions as proposed in Cho and Yeom (2007) for imaging seepage in an embankment. Those cross-line measurements are based on dipole-dipole configurations as commonly used in cross-borehole surveys. We illustrate the method by investigating the subsurface geometry in a karstic environment for a future wind turbine project. We first describe the field site and the geological context. Then, the designed acquisition and processing procedure is described and assessed by numerical benchmark modeling, using a synthetic model. We applied our validated methodology to the field case to image the top of the unaltered limestone formation and to characterize the 3D geometry of karst features. We then discuss the importance of cross-line measuring and analyze its capability and optimal setup for correct subsurface geometry imaging.

2. Field site

The test site is located in the Couvin region, Belgium (Fig. 1). It is a large area where a wind turbine construction project is ongoing. As a preliminary study, a 2D electrical resistivity tomography profile was performed by a private company (64 electrodes, 5 m spacing, NW-SE direction) at the assumed location of each future wind turbine location. A large, medium resistivity value anomaly (150–200 Ω m) was detected beneath the location of one of the future wind turbines. This anomaly was interpreted as an entity where limestone is heavily altered and is supposedly linked to karstic phenomena present in the subsurface (see Section 2.2).

Standard geotechnical investigations (such as cone penetration tests) would provide only punctual information. Ideally, in such complex geo-hazardous environments, a 3D integrated site investigation should be executed to construct a 3D subsurface geological model which can support civil engineering and strategic design (e.g., Ismail and Anderson, 2012; Song et al., 2012). This concept was the motivation to conduct a 3D ERT survey at the location of the future wind turbine.

2.1. Geology

The survey site region is located at the southwestern edge of the synclinorium of Dinant (Fig. 1), a geological structure composed of a

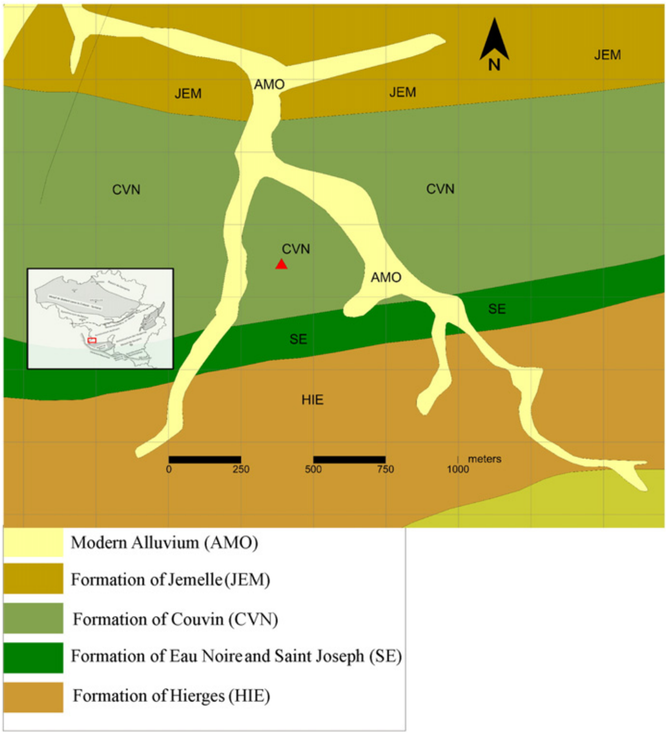

Fig. 1. Geological map of the site (red triangle) area (modified after Marion and Barchy, 1999a).