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Improvement of 2D ERT measurements conducted along a small earth-filled dyke using 3D topographic data and 3D computation of geometric factors

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ABSTRACT

In the framework of earth-filled dykes characterization and monitoring, Electrical Resistivity Tomography (ERT) turns out to be a commonly used method. 2D sections are generally acquired along the dyke crest thus putting forward the question of 3D artefacts in the inversion process. This paper proposes a methodology based on 3D direct numerical simulations of the ERT acquisition using a realistic topography of the study site. It allows computing ad hoc geometrical factors which can be used for the inversion of experimental ERT data. The method is first evaluated on a set of synthetic dyke configurations. Then, it is applied to experimental static and time-lapse ERT data set acquired before and after repair works carried out on a leaking zone of an earth-filled canal dyke in the centre of France. The computed geometric factors are lower than the analytic geometric factors in a range between −8% and − 18% for measurements conducted on the crest of the dyke. They exhibit a maximum under-estimation for intermediate electrode spacings in the Wenner and Schlumberger configurations. In the same way, for measurements conducted on the mid-slope of the dyke, the computed geometric factors are higher for short electrode spacings (+18%) and lower for lower for large electrode spacings (−8%). The 2D inversion of the synthetic data with these computed geometric factors provides a significant improvement of the agreement with the original resistivity. Two experimental profiles conducted on the same portion of the dyke but at different elevations also reveal a better agreement using this methodology. The comparison with apparent resistivity from EM31 profiling along the stretch of the dyke also supports this evidence. In the same way, some spurious effects which affected the time-lapse data were removed and improved the global readability of the time-lapse resistivity sections. The benefit on the structural interpretation of ERT images remains moderate but allows a better delineation of the repair work location. Therefore, and even if the 2D assumption cannot be considered valid in such a context, the proposed methodology could be applied easily to any dyke or strongly 3D-shaped structure using a realistic topographic model. It appears suitable for practical application.

1. Introduction

Earth-filled embankments are worldwide-spread structures. Some of them might be older than several centuries and, consequently, their geotechnical condition might be very poorly known. As such, there is a need for rapid, cost-effective and noninvasive tools, making geophysical methods adequate for such investigations. In the past decades, Electrical Resistivity Tomography (ERT) has become one of the most popular geophysical techniques to investigate such structures. It allows imaging in high-resolution the depth to the bedrock and the lateral variation of the interface between the dyke and its substratum (Cardarelli et al., 2010; Minsley et al., 2011; Cardarelli et al., 2014; Bièvre et al., 2017). This technique can also provide information about the internal structure of the dykes (Weller et al., 2006; Cho & Yeom, 2007; Niederleithinger et al., 2012). Measurements can also be repeated to provide the evolution of resistivity with time. This time-lapse approach is used to derive the evolution of a physical parameter to which resistivity is sensitive (temperature, clay content, moisture, etc.). This approach was used by several authors to locate seepage paths within earth dykes (Sjödahl et al., 2008; Sjödahl et al., 2009; Weller et al., 2014).

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However, for practical considerations such as cost-effectiveness and available space, electrodes are generally spread along the dyke crest. This configuration might appear very well suited to try to detect weak zones, where seepage paths could exist at depth and which are generally perpendicular to the dyke stretch and, consequently, to the electrode spread. Classically, dyke crests are considered as flat structures and analytical geometric factors, defined for infinite flat half-spaces, are used to compute apparent resistivity. Thus, data are processed using 2D inversion algorithms which do not take into account the 3D geometric effects caused by the topography, and the 3D geophysical effects caused by the subsurface resistivity distribution. The effect of topography was reported and evaluated in 2D since more than thirty-five years in the pioneering works of Fox et al. (1980). However, such effects remain little studied specifically in the context of dykes monitoring. Hennig et al. (2005) studied the effect of topography on resistivity measurements for several protocols and for profiles acquired perpendicular to the stretch of a dyke. Using Finite Element Modelling, they were able to determine a factor to correct resistivity measurements from the effect of surface geometry. A very similar approach will be used in this work. Sjödahl et al. (2006) numerically studied a 220 m wide and 60 m high dam made of a till core, a surrounding filter zone, and a rock cap. Using a 2.5 D approach (a 2D model with a constant geometry in the third dimension), they showed that the 3D geometric setting affected the data. When compared with a 1D model, the computed resistivity increased from around 20% to almost 40% as a function of electrode spacing. They also showed that the variation of the water level in the reservoir had an effect on the computed resistivity. Their work finally showed that it is possible to assess these effects using numerical computation. Similarly, Cho et al. (2014) numerically studied topographic effects on a 86 m wide and 20 m high earth dyke. They evidenced resistivity variations of up to 30% caused by water level fluctuations. They chose to build a combined reference model to invert experimental time-lapse data. This strategy allowed to detect a damaged zone for low water level change but failed to image it for large water level change. Recently, Fargier et al. (2014) studied numerically and experimentally such geometric effects on a smaller structure, namely an earth-filled dyke with a height of 6 m and a width of 28 m. They confirmed the existence of 3D geometric effects and proposed to correct them by using the computation of topographic (i.e. surface geometry) effects but also by using a priori information regarding the 3D resistivity distribution of the sub-surface.

Bièvre et al. (2017) recently reported an integrated geophysical (seismic and resistivity) and geotechnical study of a small earth-filled canal dyke (10 m wide at the base and a maximum height of 10 m) located in the centre of France. This study allowed to define precisely the geotechnical configuration of the dyke and also to locate a seepage path at a depth of around 3.4 m below the dyke crest using ambient vibrations. However, static ERT failed to locate this seepage and even exhibits a seemingly incoherent discrepancy between parallel profiles conducted at different elevations.

The aim of this study is first to numerically evaluate the origin of such a poor performance of ERT in the context of dykes. The direct current electrical diffusion problem is solved using 3D finite element synthetic models simulating the studied dyke. Increasing levels of complexity are considered to evaluate the effect of topography and of 3D/4D resistivity distributions (e.g. a change in the water level in the canal). Such an approach allows computing custom geometric factors and to assess their benefit on the 2D inversion. The second objective is to process experimental static and time-lapse data using these computed geometric factors before a classical 2D inversion. The variation of the water level in the canal induced time-varying topography and resistivity variations during the study. These corrected results are then compared with the results of a classic 2D time-lapse approach in order to put forward the ability of this approach to retrieve more realistic resistivity which can help imaging and monitoring earth dykes more accurately.

2. Materials and methods

2.1. Study site

The study site is located in the centre of France. The dyke was built during the first half of the XIXth century and is made of a heterogeneous mixture of silts, sands, and gravels which overly Jurassic marly limestones (Fig. 1a and b). The dyke's crest is 4 m large with a maximum height of 10 m. A 5 m-long breach occurred in 2007, which supposedly originated from internal erosion phenomena. The study area is located 1.5 km North of the breach, in an area where two apparently cylinder-shaped leakage zones (LZ) were visually identified (Fig. 1a). LZ1 and LZ2 showed water flow rates of around 250 l/min and of around a few tens of l/min, respectively. A 127 m-long profile was specifically selected on the crest of the dyke in order to test different surface geophysical methods (refraction seismics, P-wave and S-wave tomography, surface waves inversion, Electrical Resistivity Tomography). It corresponds to electrical profile EP1 in Fig. 1 and, in the following, all distances are expressed with reference to this profile. This profile was selected because it covered two leakage zones (a major one at 35–45 m and a smaller one at 90–100 m along the profile and at depths of 3.4 m and 1.5 m below the top of the dyke, respectively; Fig. 1). Results were reported by Bièvre et al. (2017) and showed that these classical methods are able to retrieve the geometry of the dyke over the bedrock but failed to locate the two leakage zones. On the contrary, passive seismic monitoring allowed to localize LZ1 below the dyke crest, at a distance of 37 m $\pm$ 0.4 m along EP1 and a depth of 3 m $\pm$ 0.4 m. This depth corresponds to the interface between the dyke itself and the underlying bedrock. Using the same approach, LZ2 was not detected. It was then suggested that LZ1 was subject to turbulent water flows which allowed to generate energetic enough seismic signals.

2.2. 2D experimental ERT measurements

The 128 electrodes used for profile EP1 were left into the ground to periodically monitor the evolution of resistivity. A second ERT profile labelled EP2 (location in Fig. 1) was acquired on November the 10th 2010. It is located along the road, around 1.8 m below the top of the dyke. It consisted of 64 electrodes with a constant electrode spacing of 1 m. Four further roll-along allowed to gather a 127 m-long profile, with the same characteristics as EP1. The canal was emptied to repair the leakage zones (by injecting clays) and was then refilled. These work operations lasted four weeks between November the 08th and December the 12th 2010.

Resistivity measurements were conducted with a single-channel ABEM Terrameter LS using 64 electrodes at a time. Four further roll-along steps with a shift of 16 electrodes were needed to complete the measurements. Given the technical limitations (single-channel resistivimeter), the Wenner-Schlumberger configuration was chosen since it provides both good vertical resolution and good signal-to-noise ratio (SNR). The vertical resolution was favoured to better detect the interface between the dyke and the bedrock. The good SNR was also chosen in order to detect even slight changes between time steps. To achieve a sufficiently satisfying lateral resolution, the number of measurements was set to a relatively high number (see further). The spacing between potential electrodes (a spacing) was set between 1 m and 21 m. For the Schlumberger configuration, the n factor was set between 2 and 7. Only the measurements in common between the sequences were kept for time-lapse processing. A total number of 3558 measurements was obtained, 983 of which were in a Wenner configuration (27% of the measurements).

Experimental injection parameters were set to 100–400 mA and 100–200 V for the required current and voltage between dipole AB, respectively. These parameters allowed to measure voltages between 0.05 V and 6 V for dipole MN. Most measurements indicated contact