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Integration of geotechnical and geophysical techniques for the characterization of a small earth-filled canal dyke and the localization of water leakage

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ABSTRACT

This paper investigates the combined use of extensive geotechnical, hydrogeological and geophysical techniques to assess a small earth dyke with a permanent hydraulic head, namely a canal embankment. The experimental site was chosen because of known issues regarding internal erosion and piping phenomena. Two leakages were visually located following the emptying of the canal prior to remediation works. The results showed a good agreement between the geophysical imaging techniques (Electrical Resistivity Tomography, P- and SH-waves Tomography) and the geotechnical data to detect the depth to the bedrock and its lateral variations. It appeared that surface waves might not be fully adapted for dyke investigation because of the particular geometry of the studied dyke, non-respectful of the 1D assumption, and which induced depth and velocity discrepancies retrieved from Rayleigh and Love waves inversion. The use of these classical prospecting techniques however did not allow to directly locate the two leakages within the studied earth dyke. The analysis of ambient vibration time series with a modified beam-forming algorithm allowed to localize the most energetic water flow prior to remediation works. It was not possible to detect the leakage after remediation works, suggesting that they efficiently contributed to significantly reduce the water flow. The second leakage was not detected probably because of a non-turbulent water flow, generating few energetic vibrations.

1. Introduction

Earth-filled canal embankments play several functions. Their role is to ensure shipping, water transport and water storage. Depending on their degree of impermeability, these dykes present the particularity of containing a more or less permanent hydraulic head. As such, they are prone to internal erosion phenomena, such as leakage and piping, which may lead to breaching (Foster et al., 2000; Fell et al., 2003). Furthermore, these structures might be older than several tens of years with very few available geotechnical data. Finally, these linear infrastructures may be stretched over up to several thousands of km per country (e.g. 9000 km of embankments in France according to the French Association of Embankments' Managers; france-digues.fr). As such, rapid and cost-effective methods are needed to assess the geotechnical conditions of these structures, to locate heterogeneous and/or weak zones and to optimize the location of geotechnical prospecting (drilling and in situ tests).

Since the pioneering works of Ogilvy et al. (1969) and due to technological improvements in the past decades, geophysical methods have been increasingly used to assess the geotechnical and hydrogeological setting of earth dykes. These methods have been used to characterize both the internal architecture of dykes (geometry, lateral variations, etc.) but also to try to localize specific anomalies such as internal erosion pipes. To achieve a first qualitative zoning, in terms of architecture and geometry, it is generally recommended to apply first rapid and efficient methods such as Slingram and/or Airborne ElectroMagnetic (AEM) induction techniques (Fauchard and Mériaux, 2007; Royet et al., 2013). When heterogeneous zones are detected, quantitative imaging techniques (among others: electrical resistivity, seismic refraction, ground-penetrating radar (GPR)) are then applied to try to locate in two dimensions (2D) defaults within the dyke (Fauchard and Mériaux, 2007; Niederleithinger et al., 2012). Among all geophysical techniques, Electrical Resistivity Tomography (ERT) is the most

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commonly used to characterize dykes. It has been applied to image the depth to the substratum and its lateral variation (Cardarelli et al., 2010; Minsley et al., 2011; Cardarelli et al., 2014) as well as the internal variations or structures of dykes (Weller et al., 2006; Cho and Yeom, 2007). Time-lapse ERT has also been successfully used to image the internal evolution of dykes and to detect leakage and seepage path (Sjödahl et al., 2008; Sjödahl et al., 2009; Weller et al., 2014). On the one hand, the advantages of ERT are that the method is fast, easy to deploy and is sensitive to multiple parameters (among others, moisture and clay content) and to their change with time (Telford et al., 1990). On the other hand, the method suffers from non-uniqueness, which means that the images need to be calibrated with external information to produce a geotechnical interpretation (Telford et al., 1990). Among all other imaging techniques, there also exists a trade-off between depth and resolution. Another electrical method, namely Self Potentials, has been largely used on earth dykes. It is a passive electrical technique which was originally applied to the detection of leakage from water reservoirs by Ogilvy et al. (1969) and Bogoslovsky and Ogilvy (1970). Recently, Bolève et al. (2011) successfully localized seepages using Self Potentials completed with salt injection within the reservoir. Bolève et al. (2012) also used Self Potentials in parallel with hydro-acoustic measurements to detect and localize leakages within a dyke.

Seismic methods have been less used to characterize earth embankments. P-wave velocity (Vp) is highly sensitive to the water content and hence preferentially detects the water table within the dyke body (Ikard et al., 2015). Using P-wave refraction over a non-saturated earth dam, Kim et al. (2007) were able to locate low-velocity zones, which they associated to previously identified seepage entry path zones. P-wave refraction and/or tomography was also found to be adapted to locate the depth to the bedrock (Cardarelli et al., 2010). S-waves are less sensitive than P-waves to the presence of water. They also have the advantage of offering a better resolution than P-waves. S-wave velocity (Vs) imaging has however been poorly reported. This might be linked to the difficulty of generating energetic S-waves which results in a poor signal-to-noise ratio (SNR). Cardarelli et al. (2014) conducted both P- and S-waves tomography on an earth-filled dam which allowed them to evaluate the Poisson coefficient of the soil. Surface waves (SW) inversion has been recently applied for dyke characterization (Cardarelli et al., 2010; Cardarelli et al., 2014). It has been used preferentially to Vs imaging in order to retrieve vertical Vs profiles. Rayleigh SW offer the advantage of being recorded at the same time as P-waves, provided geophones with a sufficiently low cut-off frequency are used (Socco and Strobbia, 2004). SW inversion provides 1D Vs profiles where Vs varies only as a function of depth. The gathering of several 1D profiles spread along the dyke might allow an interpretation in terms of pseudo-2D Vs image. However, the 1D assumption might not be respected on dykes, considering the complex surface morphology of these structures when compared with a flat half-space. Karl et al. (2011) studied numerically these effects and concluded that they were insignificant for dykes with a base width-to-height ratio larger than four. Recently, the application of seismic ambient noise monitoring to a controlled laboratory-scale experiment and an in situ experiment allowed Planès et al. (2015) to detect significant velocity variations (a drop by around 20%) which they attributed to a piping process developing through a dam. Other techniques, such as acoustic emissions localization have been employed to localize leakages, using hydrophones (Bolève et al., 2012) or geophones on the dyke (Rittgers et al., 2015).

Other geophysical methods have also been applied for the location of pipes, voids and internal erosion paths within earth dykes. GPR was successfully applied to locate pipes and voids (Carlsten et al., 1995; Xu et al., 2010; Antoine et al., 2015) at several sites. However dykes generally contain clays and silts which prevent the systematic application of GPR.

The aim of this study is first to evaluate and compare the results obtained with classical active geophysical methods (refraction seismics, first arrivals tomography, electrical resistivity tomography) to characterize the geometry of a small (a few meters in height and width) earth-filled dyke with a permanent hydraulic head. The second objective is to test the ability of these methods to detect weak zones where known leakages take place. Remediation works on the chosen study site induced an emptying of the canal. This allowed to precisely locate the origin of the flows from within the canal. An extensive geotechnical prospecting, including drillings, in situ tests and laboratory tests, was conducted to calibrate the geophysical results. Finally, the third objective of this paper is to expose the results of leakage localization obtained with an ambient vibration measurement feasibility test. This test was not first designed to process ambient vibrations. It however provided promising results which will be presented in this paper.

2. Study site

The 56 km-long Canal de Roanne à Digoin (CRD) was built during the first half of the 19th century between 1830 and 1836. Its role is to ensure both shipping (freight and tourism) and water feeding to the “canal latéral à la Loire”, a 200 km-long canal which allows to skip shipping on the Loire river, subject to floods and droughts. In the study area (Fig. 1a), the dyke of the CRD is made of a heterogeneous mixture of clays, silts, sands and gravels. It relies upon Jurassic marly limestones (Fig. 1b), the top of which is supposedly more or less weathered and decalcified (Bouiller et al., 1990). The dyke imperviousness is ensured by a concrete facing at the base of the canal (Fig. 1b). From a geometrical point of view, the dyke is 4 m wide on top and 18 m wide at its base, with a maximum height of 10 m. This corresponds to a base width-to-height ratio of around 1.8. The lateral slopes are 33° (3 horizontal units per 2 vertical units). An intermediate berm, towards the east and located between 1.5 m and 3 m below the dyke crest, serves as a road. The site was chosen because of known issues with regard to internal erosion phenomena, namely leakage and piping. A 5 m-long breach occurred in 2007 (Fig. 1c) 1.5 km south of the study site, which supposedly originated from internal erosion phenomena.

The study site is located in an area where two leakage zones were visually identified at the base of the dyke (Fig. 2). A 127 m long profile, covering two leakage zones (labelled LZ1 and LZ2 and located 34.5 m and 95 m along the profile, respectively) was specifically selected in order to test different geophysical and geotechnical methods (Fig. 2) between October 2010 and May 2011. The canal was emptied in November and December 2010 for improvement works. They allowed to precisely locate the flow inlets inside the dyke. They are referred to as leakage entry paths 1 (LEP1) and 2 (LEP2) in Fig. 2.

Fig. 3a and b show photographs of LZ1 and LZ2, respectively. Pictures were taken in October 2010 and the water height into the canal was 3.4 m. Pictures show that the pipes are pluridecimetric in diameter, with estimated flow rates of around 250 l/min for LZ1 (Fig. 3a) and of a few tens of l/min for LZ2 (Fig. 3b). Fig. 3c and d were shot in mid-November 2010, during the emptying of the canal and show photographs of LEP1 and LEP2, respectively. LEP1 is located 35.5 m along the profile. It is positioned at the base of the canal, 3.4 m below the top of the dyke and it is around 0.2 to 0.3 m in diameter. LEP2 is located 98 m along the profile. It is positioned around 1.5 m below the top of the dyke and it is also 0.2 to 0.3 m in diameter. The location of LEP and leakage zones are coincident between each other and, from a planimetric point of view, suggest a more or less straight path, from LEP1 to LZ1 and from LEP2 to LZ2, through the dyke (Fig. 2).

3. Investigation methods

This study included the performing of an extensive geotechnical investigation on the dyke, along with geophysical prospecting, over a period of 6.5 months. The location of the geotechnical and geophysical experiments is presented in Fig. 2. The time schedule of each experiment is exposed in Fig. 4 along with daily rainfall and hydrostatic levels in boreholes d1 and d3. Table 1 details the specifics of each experiment. Most geotechnical (drilling, coring, in situ and laboratory tests, nuclear