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Electrical resistivity tomography to understand clay behavior during seasonal water content variations

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ABSTRACT

Problems with foundations highlight a lack of understanding surrounding factors which influence ground movements during wet–dry cycles (Vincent, 2009). To address this issue, geotechnical characterizations of a clayey formation can be used to identify significant variability in lithological facies, both vertically and horizontally over very short distances. Soil heterogeneities explain in this case a wide range of geotechnical parameters and weak correlations between them, assessed on soil behavior observed on site. This paper focuses on soil water deficits and benefits over time, related to soil composition in a heterogeneous clay formation through the use of electrical resistivity tomography (ERT). Electrical resistivity tomography and time domain reflectometry (TDR) were used simultaneously to measure resistivity and soil moisture at an experimental field site with the unique objective of qualifying soil moisture in this first stage of the study. The resistivity variations obtained from ERT were compared to local effective rainfall and soil moisture measurements from time domain reflectometry (TDR) down to a depth of 3 m. Results show the potential of qualifying soil water content variations over the seasons, and especially of detecting a rapid increase in humidity thanks to spatial soil heterogeneity at a decimetric scale. ERT proves to be a useful method of delineating soil facies based on their drying and humidification behavior.

1. Introduction

The engineering properties of alluvium deposits can vary greatly. Terraces make ideal construction sites as they are relatively flat, are not subject to flooding and are typically underlain by sand and gravel. However, in areas where there were slow-moving streams, very thick deposits of clayey silt can occur, giving rise to a lack of bearing strength for large loads. Where such conditions exist, pilings are extensively used in the construction of multi-story buildings. A further problem resulting from these alluvial deposits is the delineation of specific sand and clayey lenses; if slabs or continuous spread footing are distributed onto heterogeneous layers, differential settlements can occur (Houy et al., 2005; Denis et al., 2011). Engineering problems associated with clayey soils are typically due to their low shear strength, making these kinds of soils very hazardous for shallow foundations. Expansive clayey soils are also hazardous due to the expansion and contraction accompanying soil moisture changes, causing damage when the soil shrinks on drying or when it expands as it becomes wet, and these resulting soil movements can affect the structural integrity of houses. Houses with inadequate (i.e. shallow) foundations develop damage ranging from sticking doors and hairline cracks in the plaster to their complete destruction (Vincent, 2009; Andrieux et al., 2011). Expansive soils owe their characteristics to the presence and arrangement of swelling clay minerals, determining their ability to swell and shrink after annual moisture changes. Numerous residential constructions, both recent and old, with no previous history of even minimal differential movements, have developed foundation problems over a very short period of time due to changes in moisture content during extended periods of drought (Vincent, 2009). To address this problem, the swell–shrinkage behavior has been investigated in situ, and specifically on a Plio-Quaternary clayey formation (Brach formation) responsible for around a hundred structural issues in buildings since 1989 in the suburbs of Bordeaux (south of France) (Chrétien, 2010; Andrieux et al., 2011).

Localization of soil facies variation and seasonal water content measurement remain the two principal elements in traditional geotechnical investigation. Electromagnetic measurements obtained through time domain reflectometry (TDR) allow reasonably accurate water content measurements (Robinson et al., 2003; Bittelli et al., 2008); the disadvantages of these measurements are related to the limited volume of investigation and to the installation itself which can alter the soil structure. Geophysical methods do not affect the soil structure and the resulting measurement overlays a first level of soil spatial variability at a decimetric scale depending on the spacing between electrodes. Electrical resistivity can be adapted to assess the variability of material property like the water content, notably in the framework of investigation prior to geotechnical sounding (De Benedetto et al., 2012; Lataste

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et al., 2012; Guerrero et al., 2013). Electrical resistivity tomography (ERT) is a tool that can monitor moisture variations within geological materials (Zhou et al., 2001; Brunet et al., 2010; Bourennane et al., 2012). The relationship between electrical resistivity and humidity was clearly understood by Archie (1942), and used in laboratory applications (Kalinski and Kelly, 1993) as well as on site (Rapti-Caputo et al., 2009). On material with clay content, Archie's law must be completed by a second part, to take into account the surfacic conductivity within clay (Simandoux, 1963; Waxman and Smits, 1968). In any case, whatever the law considered, the influence of water content is clear and, when increasing, leads to decreases in resistivity. Links between resistivity variations and water distribution in soils were done through numerous studies. It demonstrates the effectiveness of this approach for studying transient phenomena within the scope of geotechnical matters (Santarato et al., 2011), for seepage monitoring in earth embankments (Johansson and Dahlin, 1996; Sjödahl et al., 2008), for studying the dynamics of aquifers (Brunet et al., 2010; Fowler and Moysey, 2011), or of soils (Benderitter and Schott, 1997). These studies are based on the comparison of ERT sections carried out on different occasions, identifying changes in soil properties. Because of the potential of this approach, it is now widely studied (Rein et al., 2004; Samouellian et al., 2005; Schwartz et al., 2008). Previous studies (Binley et al., 2002; Hagrey et al., 2004; Robinson et al., 2012) deal with the moisture dynamic of soil and were able to highlight the impact of its environment on soil properties over time. We want to include the concept of spatial variability in addition to the seasonal variations (Besson et al., 2004) to understand the interaction between these two scales of variations (spatial and temporal) on the behavior of expansive soils. Without aiming at calibration between moisture and resistivity we will use the sensitivity of electrical resistivity tomography to monitor soil water deficits and benefits over time. We focus on water content variations in relation to lithological composition in a heterogeneous clay field. This paper presents (i) the test site and the data collected in situ, (ii) the ERT method and investigation over time, (iii) the results discussed in comparison with TDR measurements and lithological soil structure at the profile scale.

2. Field site

The area under investigation is located in the west of Pessac, a town in the suburbs of Bordeaux (France). The region is characterized by an oceanic climate, with a 984 mm/year annual mean rainfall recorded by the local MeteoFrance rain gauge for the period 1971–2000. There is no topography, only small trees, and there are no buildings on the site. This area is located on the Brach geological formation (Thierry and Breysse, 2006) (Figure 1), composed mainly of gray-blue clayey soils with orange marblings and dating back to the upper Pleistocene (Platel and Astruc, 2000). This clayey formation is composed mainly of kaolinite (60 to 80%) and smectites (10 to 25%). Geological drilling campaigns dating from December 2006 to August 2008 show that, within this formation, clay–sandy lenses could be the consequence of a fluvial environment during the Plio-Quaternary period, with the partially cemented brown sandstone called “Alios”, the ferruginous sandstone typical of the “Landes de Gascogne” (Gourdon-Platel, 1975; Tastet and Pontee, 1999). Sand filled the cracks in clayey soils and made the clay soils less impermeable, allowing temporary water flows through sandy lenses between a depth of 2 and 5 m. The water level was 15 m below ground surface, which is deep enough not to be relevant in this case. The bedrock is located between a depth of 15 and 25 m.

3. Soil characterization

3.1. Geotechnical characterization

Mechanical properties of the soils were characterized by geotechnical analysis of 66 samples collected from destructive and core drillings on the site at different depths: natural water content (w_i), percent finer than 2 μm (2 μm), Atterberg limits (PI), methylene blue absorption test method (Vb) on particle size of 400 μm. Then we focused on the investigation of the swelling and shrinkage characteristics on intact clayey samples: swelling and compressibility parameters (compressive index Cc, swelling potential ε_g, swelling coefficient Cg, initial void ratio e_0, dry density γ_d/γ_w, permeability coefficient at saturation k_0). Table 1 gives the minimum and maximum values obtained by traditional geotechnical analysis and consolidation tests at different depths and for two distinct soil facies (A/BOG: clayey facies and SA: sandy–clay facies).

Table 1 shows that the samples (collected in the same area) differ widely in their clay content (from 27 to 74%) with a mean of 40%. Soils present medium to high liquidity limits with a maximum plasticity index above 57%, and high blue methylene values, up to 11 (mean of 6). These results reflect the heterogeneity of the geotechnical parameters of

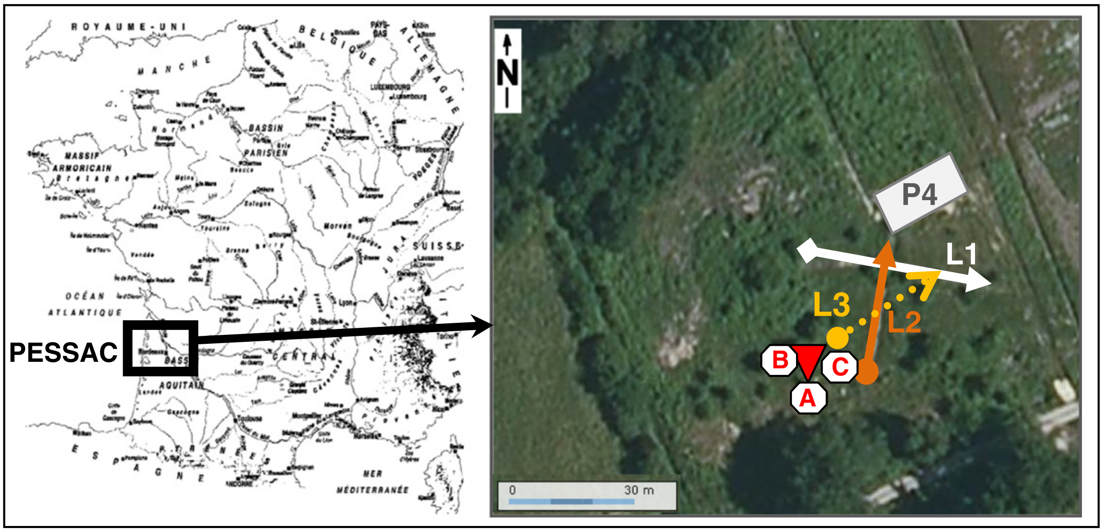

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Fig. 1. Location of the field site (Google Earth, 2010) and experimental in situ monitoring systems: ▼rain gauge and temperature probes at depths of 0.50, 1, 2, 3 and 5 m; ⬡TDR tubes; ▭geological excavation; and L1, L2 and L3: ERT profiles.