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Research paper

Characterizing drying-induced clayey soil desiccation cracking process using electrical resistivity method

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ABSTRACT

Desiccation cracking process negatively impacts both mechanical and hydraulic properties of clayey soils. Traditional methods applied for the characterization of soil cracking behaviors are mainly based on visual inspections or destructive approaches. The electrical resistivity method provides a non-destructive, sensitive and continuous evaluation of the spatiotemporal variations of many soil physical properties. In this study, an integrated experimental setup is configured to simultaneously capture the evolution of temperature, relative humidity, water content, crack morphology, and apparent electrical resistivity in clay during continuous drying. Apparent electrical resistivity measurements at 1.0 cm electrode spacing are carried out to detect the initiation, propagation and coalescence of desiccation cracks. Image processing quantitatively describes the geometrical characteristics of shrinkage surface crack patterns. Experimental results indicate the strong correlation between the measured apparent electrical resistivity and cracking behavior of soil. As water content decreases during drying, the apparent electrical resistivity of initially saturated clayey soil decreases first before the onset of desiccation cracking, and then transits into the increasing trend. The evolution of apparent electrical resistivity in clayey soil is dominated by two competing effects, with one originated from the volumetric shrinkage-induced closer packing of soil fabric and higher concentration of ions in pore fluids, and another from the evaporation-induced water loss associated with hydration film contraction and desiccation crack insulation. The electrical resistivity method is an effective technique to characterize the development of desiccation cracks, and particularly reliable to map their positions. This study is expected to improve the fundamental understanding of desiccation cracking mechanisms in soils and provide insights on soil characterizations for enhanced stability and performance of earthwork structures.

1. Introduction

Global climate change has driven the more frequent occurrence of extreme drought periods in many regions, where soils experience significant amount of water loss and considerable volumetric shrinkage under such conditions. Soil shrinkage during drying is generally associated with the progressive formation of cracks, causing severe degradation to both hydraulic and mechanical properties of soils (Morris et al., 1992; Tang et al., 2010; Chaduvula et al., 2017). Crack networks considerably modify the soil structure and impact its hydraulic behavior by creating preferential flow paths for fluids and contaminant transport (Chertkov and Ravina, 1999; Horgan and Young, 2000; Chertkov, 2000; Kalkan, 2009; Tang et al., 2011a). Mechanical responses of soils subjected to desiccation cracking are also significantly compromised, resulting in impaired strength, excessive deformation, and increased compressibility. The combined effects are responsible for the reduced performance or even ultimate failure of buildings and earth structures such as slopes, flood embankments, earthen heritages, buffers and barriers for nuclear waste isolation, and liners and covers for landfill (Boynton and Daniel, 1985; Miller et al., 1998; Yesiller et al., 2000; Albrecht and Benson, 2001; Philip et al., 2002; Tang et al., 2012; Jones et al., 2014; Zhang et al., 2016).

With the heightened attention, a number of investigations have been carried out to better understand the underlying mechanism of desiccation cracking processes and assess their potential hazard to infrastructures (Abu-Hejleh and Znidarčić, 1995; Konrad and Ayad, 1997; Velde, 1999; Yao et al., 2002; Nahlawi and Kodikara, 2006; Rodríguez et al., 2007; Péron et al., 2009; Tang et al., 2011b, 2011c; Shin and Santamarina, 2011). Mapping and quantifying the geometrical structures of desiccation crack networks is a major concern when assessing

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their influences on the coupled hydro-mechanical behavior of soil (Tang et al., 2008), inferring soil's performance under wetting and drying cycles (Perrier et al., 1995), and investigating past stress-strain responses and predicting future integrity and reliability of soil (Preston et al., 1997).

Field-scale inspection of soil cracking commonly resort to visual observations on soil surface that would require surveyors to walk along the entire earth structures such as embankment and slope for crack observation and measurement (Kleppe and Olsom, 1985; Dasog and Shashidhara, 1993; Morris et al., 2007), destructive techniques such as the excavation of trenches (Cooling and Marsland, 1954; Dyer et al., 2009), and nondestructive geophysical surveys such as Ground Penetration Radar (GPR) (Benson, 1995; Hinkel et al., 2001; Levatti et al., 2017) and Electrical Resistivity Tomography (ERT) (Sentenac and Zielinski, 2009; Jones et al., 2012; Chambers et al., 2012; Jones et al., 2014; Gunn et al., 2015). However, subsurface desiccation cracks especially less opened cracks can be easily overlooked during visual surveying due to dense surface vegetation, causing an underestimation of their potential hazards on the integrity of an earth structure (Jones et al., 2014). Although the actual depth and the pattern of subsurface cracks can be exposed through trenching or sampling, those invasive and destructive techniques are time-consuming and laborious, and more importantly, may disturb the original crack pattern resulting in less reliable evaluations. Therefore, non-destructive methods such as ERT and GPR turn out more popular, which overcome aforementioned limitations and can efficiently identify and characterize the extent of desiccation cracking.

It is well known that the electrical resistivity of soil, quantifying how soil resists the flow of electricity, is a sensitive reflection of many soil properties, including the nature of solid (mineralogy, shape, fabric, and size distribution), arrangement of voids (porosity, tortuosity, connectivity, pore structure), and properties of fluid (water content, electrical resistivity, solute concentration) (Archie, 1942; Keller and Frischknecht, 1966; Arulanandan and Muraleetharan, 1988; Thevanayagam, 1993; Andrews et al., 1995; Gibert et al., 2006; Chambers et al., 2012, 2014; Gunn et al., 2015; Kaufhold et al., 2015). The interplay of these factors determines the movement of anions and cations under applied electrical field, reflected macroscopically as the variation of the electrical resistivity of soil. The presence of cracks in a soil is responsible for the diverted flow of ions and a greater potential loss than it would be experienced in intact soil (Samouëlian et al., 2004; Samouëlian et al., 2005). Given the strong contrast between the electrical resistivity of a crack and of the hosting soil body, approximately differed by ten orders of magnitude, measuring electrical resistivity turns out a favorable approach for the non-destructive and continuous characterization of desiccation cracks and induced heterogeneities in soils. The suitability of using electrical resistivity method for crack detection has been confirmed by Samouëlian et al. (2003) through the study of artificially cracked silty loam. Recently, Sentenac and Zielinski (2009) and Jones et al. (2012) used the electrical resistivity method to map desiccation crack networks in compacted clays under laboratory conditions. They further applied this method on cracked flood embankments and validated its capability for crack detection at regional scale (Sentenac et al., 2012; Jones et al., 2014). However, in most cases, the electrical resistivity method was only employed to map or identify preexisting cracks in soil, ignoring the dynamic nature of crack initiation, propagation and coalescence processes resulting from continual water loss and ensuing volumetric shrinkage. Hence, it is of prior importance to capture the correlation between electrical resistivity and soil moisture content (Chambers et al., 2012; Gunn et al., 2015), and to monitor and even infer the possible cracking position and extent in the drying soil. Acquiring such information is essential to the real-time assessment of soil engineering property changes and the enhanced performance of earth structures during sustained droughts or rainfall events. However, to the authors' best knowledge, comprehensive investigations addressing the potential correlations among water evaporation, temperature, relative humidity, crack morphology and electrical resistivity remain scarce.

This study aims to characterize the fully coupled process of drying-induced water evaporation, volumetric shrinkage and cracking in a clayey soil using the electrical resistivity method. An integrated experimental configuration was set up to track the evolution of water content, electrical resistivity, and surface crack pattern in drying soils. The correlations among these tracked parameters were analyzed and discussed. The structure of this paper is organized as follows. Section 2 briefly introduces the concept of electrical resistivity method. Section 3 details the experimental preparation and testing procedure adopted in this study. Section 4 presents experimental results obtained during the drying of soil under laboratory conditions and discussed the dependence of electrical resistivity on water content and desiccation cracks.

2. Electrical resistivity measurement

Electrical resistivity method is an appealing approach in assessing the spatiotemporal variations of soil physical properties, since they are closely associated with the electrical resistivity distribution within the soil volume (Kunetz, 1966; Scollar et al., 1990). For a homogeneous and isotropic material, surface current electrodes present the profile of hemispherical electrical equipotentials (Samouëlian et al., 2005). Measurement of electrical resistivity is possible using a variety of electrode configurations, with majority requiring four electrodes (Fig. 1). A typical measurement consists of injecting artificially generated electric current I (A) into the soil through two electrodes (A and B) and measuring the resulting potential difference ΔU (V) through two other electrodes (M and N) (Scollar et al., 1990; Kearey et al., 2002). The electrical resistivity ρ (Ω-m) between M and N can be computed as:

$$\rho = \frac{\Delta U_{MN}}{I}\left(\frac{2\pi}{\frac{1}{MA}-\frac{1}{MB}+\frac{1}{NB}-\frac{1}{NA}}\right) = K\frac{\Delta U_{MN}}{I} \tag{1}$$

$$K = \frac{2\pi}{\frac{1}{MA}-\frac{1}{MB}+\frac{1}{NB}-\frac{1}{NA}} \tag{2}$$

where I is the injected current (A), ΔU_{MN} is the measured electrical potential (V) between M and N, K is a geometrical coefficient (m) accounting for the dependence of the current flow within the material on the electrode geometry, and on the arrangement of four electrodes and the test equipment (Scollar et al., 1990; Kearey et al., 2002). MA, MB, NA and NB represent the relative spacing (m) between electrodes M and A, M and B, N and A, and N and B, respectively. For uniform soil, the electrical resistivity calculated using Eq. (1) is constant and independent of electrode configurations, which is usually recognized as true resistivity. However, the presence of heterogeneity can distort current lines and equipotential surfaces significantly and thus make electrical resistivity measurement site-specific. Such results are known as apparent resistivity and provide a qualitative description of the electrical parameters of the soil.

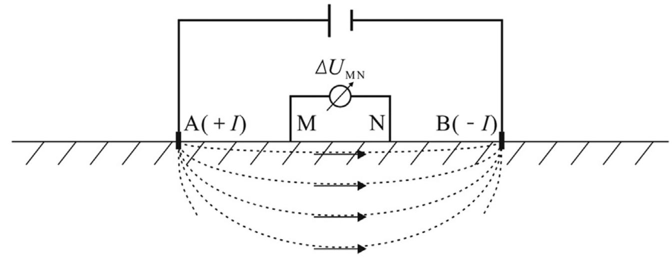

Fig. 1. Schematic view of electrical resistivity method. Dashed lines indicate the current flow through the medium.