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Research Paper

Experimental evaluation of the effects of pull rate on the tensile behavior of a clay

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ABSTRACT

Tensile strength is one of the main variables involved in the formation of desiccation fractures in clay. It is known that the drying rate affects the final amount of cracks in a soil, which points out to the potential influence of rate effects in soil cracking. The effects might be related to variations in the tensile strength affected by different shrinkage rates. A limited amount of investigations have looked at the impact of strain rate on the tensile strength of soil. This study examines the combined effects of pull rates and high water contents on the tensile strength of a clay. Particle Image Velocimetry analysis was also carried out on pictures taken during the tests to examine the strains generated. It was found that the effect of pull rate on the tensile strength of the clay was negligible compared to the effect of the water content. Pull rate did affect the stiffness response of the soil. The findings revealed that the influence of the evaporation rate on soil fracturing might be related more to the rate dependency of the stiffness rather than to significant changes in tensile strength.

1. Introduction

The development of cracks in drying soil is of special importance when trying to understand its desiccation characteristics, volume change and variations in permeability. Cracks not only increase the evaporative area, but also serve as a path for water movement and oxygen intrusion. In addition, soil fracturing affects the performance of geotechnical structures, such as the permeability of clay liners, buffers, and the stability of foundations, dams and slopes.

As established by Corte and Higashi (1960), Nahlawi and Kodikara (2006) and Peron et al. (2009), soil cracking is the result of the constrained shrinkage of the soil. Tang et al. (2010) indicated that the development of suction during the drying of the soil is the driving force behind shrinkage and cracking, which is the direct consequence of the water loss during evaporation. At the same time, evaporation also influences the rate at which the suction develops (Kayyal, 1995; Tang et al., 2010). As suction arises, tensile stresses are produced in the soil, with fracturing occurring once the tensile stresses reach the tensile strength of the material (Corte and Higashi, 1960). Trabelsi et al. (2012) pointed out that the tensile strength was not only a function of the water content of the soil, but it was also related to the suction. During the drying process, the rise in suction generates an increase in the cohesion between the soil particles, which at the same time produces an increase in the tensile strength. Peron et al. (2009) suggested that the crack initiation was directly related to the moment at which the air entry value of the soil was reached. Shin and Santamarina (2011) assumed something similar, linking the air intrusion into the pores to crack initiation. These observations lead to the conclusion that there is a direct association between the tensile strength and the water retention properties of the soil.

Laboratory experiments performed on evaporating clay samples have shown that crack initiation and intensity are dependent on several factors, such as soil thickness, drying speed and initial water content (Corte and Higashi, 1960; Kodikara et al., 2000; Nahlawi and Kodikara, 2006; Tang et al., 2008; Tang et al., 2010; Costa et al., 2013). Tang et al. (2010, 2008) and Costa et al. (2013) were able to quantify the influence of the desiccation rate on the amount of cracks produced by drying layers of equal thickness at different rates, with layers under faster drying exhibiting more fractures than the ones under a slow drying regime. These investigations suggest that there is a drying rate (i.e. shrinkage rate) dependency related to one of the factors taking part in the fracture generation process. A possible explanation is a strain rate dependency of the tensile strength in soil.

Several laboratory studies have been carried out to examine the tensile strength of soils. Most of that research has been performed in clays, or in clay, silt and sand mixtures. The methods employed in the investigations can be divided into two kinds: indirect and direct tests. Indirect methods generate tension indirectly by applying other forces. The results are evaluated and interpreted relying on assumptions of the stress distributions to obtain the resultant tensile forces. The most

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common indirect tests used are the Brazilian test (Blazejczak et al., 1995; Hallett et al., 1995; De Souza Villar et al., 2009; Beckett et al., 2015), the three point bend test (Haberfield and Johnston, 1989; Hallett and Newson, 2001; Wang et al., 2007; Yoshida and Hallett, 2008), the four point bend test (Hallett and Newson, 2005; Wang et al., 2007), the modified double punch test (Fang and Chen, 1972; Kim et al., 2007) and the split tensile test (Fang and Chen, 1972). Other indirect tests include flexural tests (Farrell et al., 1967; Briones and Uehara, 1977), the unconfined penetration test developed by modifying the double punch test (Fang and Fernandez, 1981), the pneumatic method (Snyder and Miller, 1985) and the modified unconfined penetration test (Kim et al., 2007, 2012). Direct methods subject the soil in fact to tensile forces, making it possible to measure them immediately. Among the direct methods are the "dog bone" shaped horizontal pulling tests and similar devices (Tschebotarioff et al., 1953; Hasegawa and Ikeuti, 1966; Leavell and Peters, 1987; Mikulitsch and Gudehus, 1995; Nahlawi et al., 2004; Tamrakar et al., 2005; Tamrakar et al., 2007; Rodríguez, 2006; Rodríguez et al., 2007; Prat et al., 2008; Lakshmikantha et al., 2012; Trabelsi et al., 2012; Murray et al., 2014; Stirling et al., 2015), the hanging "dog bone" tests (Ajaz and Parry, 1974; Towner, 1987), cylindrical acrylic cell tests (Nearing et al., 1991, 1988), pulling tests on hourglass shaped samples (Ibarra et al., 2005), tensile tests in the centrifuge (Vomocil et al., 1961), uniaxially loaded soil cores (Farrell et al., 1967) and hanging cylinders (Heibrock et al., 2005). Tests on the resistance to fracture performed by measuring the fracture toughness were also done by Chandler (1984), Lee et al. (1988), Harison et al. (1994) and Prat et al. (2008).

Notwithstanding the many studies focusing on the tensile strength, a relatively small number of investigations have been carried out using different pull rates to estimate the rate dependency of the tensile strength of soil. Table 1 provides a brief summary of these studies. Fang and Chen (1972) reported that the tensile strength was not sensitive to loading rates. The observation was later confirmed by Kim et al. (2007), who detected no definite trends in tensile strength variation for different loading rates. Heibrock et al. (2005) also mentioned that pull velocities did not result in any change in the measured tensile strength in their experimental tests. Tamrakar et al. (2005) employed various constant pull rates, but they made no remark regarding their influence on the tensile strength. Nevertheless, Tamrakar et al. (2007) did address the subject by examining the tensile strengths attained with different pull rates. They noticed in their experiments that there was a variation in the tensile strength. The lowest strength values were achieved for rates between 0.1 and 0.34 mm/min, with increasing strengths for rates above and below that pull rate range. After an examination of their results, the trends and magnitude of the changes described by Tamrakar et al. (2007) do not seem to support their conclusion to a large extent. On the contrary, they seemed to confirm the conclusions by Fang and Chen (1972), Heibrock et al. (2005) and Kim et al. (2007).

Most of the previous investigations on tensile strength were performed on clayey soils at water contents below the liquid limit. However, experiments carried out by the authors looking into the reuse of clay sediments starting at high water contents, have shown that fractures can start above the liquid limit, making it crucial to reconsider the behavior of the soil in tension at high water contents.

In this study, the tensile strength of a clay was investigated in the laboratory by means of strain controlled direct pull tests. The intent was to further examine the relationship between strain rate and tensile strength at water contents below and above the liquid limit. The combined effect of initial water content and pull rate was evaluated to support the understanding of cracking soils under different evaporative regimes.

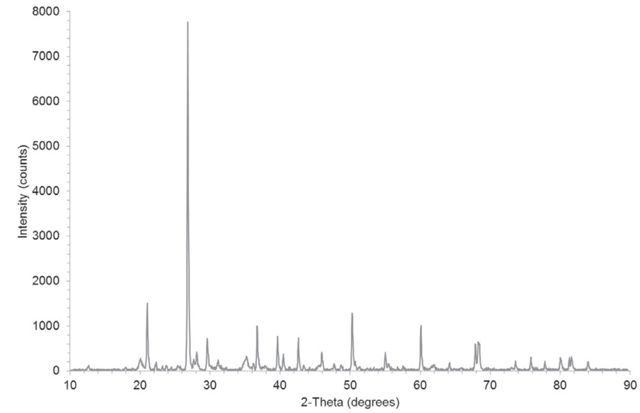

Fig. 1. X-ray diffraction pattern for filtered data.

2. Materials and methods

The investigation was carried out on a commercially available river clay, coming in blocks having an original water content of 34 ± 2%. An analysis done using a combination of X-ray diffraction (Fig. 1) and X-ray fluorescence showed that the clay was composed (by mass) of 50.2% quartz, 21% vermiculite, 16.2% muscovite, 6.8% anorthite and 5.8% calcite approximately. The physical properties of the clay are shown in Table 2. The average coefficient of consolidation and hydraulic conductivity were estimated from oedometer data on samples drilled from the block, having an initial void ratio of approximately 0.975. Average values of the coefficient of consolidation and hydraulic conductivity were $1.7 \times 10^{-8} m^2/s$ and 1.9×10^{-10} m/s, respectively. However, the tests presented in this investigation were performed on reconstituted samples from slurry at higher water contents than the "undisturbed" one. At such water contents the clay is expected to have a higher coefficient of consolidation and hydraulic conductivity, but no direct data are available.

The clay was cut into small blocks (each piece averaging approx. 20 mm^3), which were deposited in a steel container. Tap water was added until the necessary amount to achieve the desired water content was reached. Tap water was employed in order not to drastically change the chemistry of the river clay. Subsequently, the steel container was placed in a Hobart A200N mixer for 45 min, at a mixing speed of 200 rpm. The resultant slurry was put in a plastic container, where it was sealed and left for at least 24 h to further homogenize. The samples were prepared at initial average water contents of 36, 50, 62 and 77 ± 0.5%. In this study, each of the clay sample sets was tested at five different pull rates: 1, 0.1, 0.0089, 0.0015 and 0.0005 mm/min. The choice of pull speeds was based on the available range for the equipment.

Table 1
Summary of studies using different pull rates to determine the tensile strength.

Authors	Pull rate	Soil type
Fang and Chen (1972)	Between 0.03 and 2 in/min (0.762 and 50.8 mm/min)	Silty clay
Heibrock et al. (2005)	Below 0.06 mm/min	Clay
Tamrakar et al. (2005)	0.174, 0.342 and 0.882 mm/min	Clay/sand, silt/sand mixtures
Kim et al. (2007)	Between 0.1 and 1%/min (between 0.113 and 1.13 mm/min)	Sand/bentonite mixtures
Tamrakar et al. (2007)	Between 0.09 and 1.75 mm/min	Clay/silt, clay/sand, silt/sand mixtures