Engineering Geology 206 (2016) 60–70

Contents lists available at ScienceDirect

Engineering Geology

journal homepage: www.elsevier.com/locate/enggeo

Effects of wetting–drying cycles on soil strength profile of a silty clay in micro-penetrometer tests

De-Yin Wang [a], Chao-Sheng Tang [a,*], Yu-Jun Cui [b], Bin Shi [a], Jian Li [a]

[a] School of Earth Sciences and Engineering, Nanjing University, 163 Xianlin Road, Nanjing 210093, China
[b] Ecole des Ponts ParisTech, Laboratoire Navier-CERMES, 6 et 8, avenue Blaise Pascal, Cité Descartes, Champs-sur-Marne, 77455, Marne-la-Vallée cedex 2, France

A R T I C L E I N F O

Article history:
Received 31 March 2015
Received in revised form 30 March 2016
Accepted 5 April 2016
Available online 20 April 2016

Keywords:
Micro-penetrometer
Penetration resistance
Wetting–drying cycle
Strength profile
Water content
Microstructure

A B S T R A C T

A good understanding of the soil strength profile under wetting–drying (W–D) cycles is essential when studying the hydro-mechanical response of soils under the effects of precipitation and evaporation. In this investigation, initially saturated slurry specimens were prepared and subjected to three W–D cycles. A micro-penetrometer was used to characterize the effect of W–D cycles on soil mechanical behavior. Based on the obtained penetration curves (penetration resistance versus depth), the temporal–spatial evolution of soil strength under each drying path was analyzed and discussed. The results show that the developed micro-penetrometer is a simple, quick, economical and reliable tool for identification of soil strength profile. Upon drying, as the water content is relatively high, the strength of soil is low and uniform along the depth. The influence of evaporation is insignificant in the initial stage of drying even though a large amount of water is lost. After a low critical water content is reached, the strength of the upper soil layer increases rapidly, and the overall strength generally increases exponentially with decreasing water content while decreases exponentially with increasing depth. The drying induced strength exhibits obvious delayed effect in profile. With increasing W–D cycles, the strength tends to decrease. The penetration curves change from typical mono-peak pattern to multi-peak pattern after the third W–D cycle, suggesting that the W–D cycles create more defects in soil microstructure and intensify the heterogeneity of strength in profile.

1. Introduction

Soils in nature are subjected to climate change and undergo periodical wetting–drying (W–D) cycles. The W–D cycles can significantly alter soil hydro-mechanical behavior, and damage earth structures. For instance, the increase or decrease of water content in clayey soils may cause ground heave or subsidence. Pavements, embankments, buildings and other infrastructures are significantly influenced by this ground deformation. In UK, about one in five buildings are at risk by drought because they are built on clays, whose engineering properties are very sensitive to water content change (Harrison et al., 2012). The Association of British Insurers (ABI) predicts that by 2050 the annual average cost of building damage claims could increase from $450 million to $900 million, with an extreme or 'event' drought year costing $1800 million. Similar climate-related disasters also occur every year in France, USA, China, Canada and other countries (Silvestri et al., 1990; Hemmati et al., 2012). Desiccation cracks would also develop on slopes, landfill covers and clay liners as they are subjected to continuous W–D cycles (Miller et al., 1998; Tang et al., 2011). The presence of cracks can significantly weaken the soil mechanical performance (Velde, 1999; Chertkov and Ravina, 1999; Chertkov, 2000; Albrecht and Benson, 2001; Tang et al., 2010). Thus, it is vital to well understand the soil response to climate-related loading and particularly to W–D cycles. Besides the climate change, big trees adjacent to a building can often be the cause of structural problems such as cracking and sometimes movement or even cause damage to drains (Biddle, 1998), because the water-absorbing effect of tree roots can significantly change soil moisture content and its distribution, affecting the geotechnical behavior of foundation soil (Hemmati et al., 2010).

In the past decades, many tests were conducted to investigate the effects of W–D cycles on soil properties. It was found that substantial irreversible accumulation of swelling or shrinkage with significant changes in soil fabric may occur upon W–D cycles (Alonso et al., 2005; Cuisinier and Masrouri, 2005; Tripathy et al., 2009). Moreover, the irreversible volumetric deformation during W–D cycles was found to be function of compaction conditions and the subsequent variation of stress/hydration paths (Cui et al., 2002; Nowamooz and Masrouri, 2009). Goh et al. (2010) showed that the shear strength characteristics of soils under W–D cycles are different. Generally, the shear strength on drying path is higher than that on wetting path due to the hysteresis effects (Nishimura and Fredlund, 2002; Tse and Ng, 2008). The differences

* Corresponding author.
E-mail addresses: wangdeyin_nju@163.com (D.-Y. Wang), tangchaosheng@nju.edu.cn (C.-S. Tang), yujun.cui@enpc.fr (Y.-J. Cui), shibin@nju.edu.cn (B. Shi), ljspeci@163.com (J. Li).

http://dx.doi.org/10.1016/j.enggeo.2016.04.005
0013-7952/

between the shear strength on the drying and wetting paths were found to be more significant for the first cycles (Goh et al., 2014). Sivakumar et al. (2006); Nowamooz and Masrouri (2008) found that at a given suction the pre-consolidation stress on the drying path is lower than on the wetting path, and they also attributed this phenomenon to the hydraulic hysteresis during W–D cycles. Zha et al. (2013) showed that, with increasing W–D cycles, the unconfined compressive strength of soil increased first and then declined. Moayed et al. (2013) investigated the effect of W–D cycles on bearing capacity of lime-silica fume treated soil. They observed that the California Bearing Ratio (CBR) increased after the first W–D cycle, while it started to decrease during the subsequent cycles. The increase of CBR during the first cycle was attributed to the fact that enough water was provided during the first wetting path to ensure the reaction between lime, silica fume and soil. Chen and Ng (2013) performed a series of isotropic compression tests on a compacted clay subjected to several W–D cycles. They concluded that the hydro-mechanical behavior of soil was significantly influenced by the W–D history. Moreover, the desiccation cracking behavior of soil is also significantly related to W–D cycles. Tang et al. (2011) performed desiccation tests and observed that the measured cracking water content, surface crack ratio and final thickness of soil specimen increased monotonously in the first three W–D cycles and then tended to reach stabilization during the subsequent cycles.

The above-mentioned studies provided a rich database for analyzing both the volume change and mechanical behavior of soils upon W–D cycles. But most experiments were performed in a macroscopic way through oedometer tests, triaxial tests, direct shear tests, etc. These conventional macroscopic tests were usually conducted on small specimens with relative homogenous moisture distribution. Moreover, the test conditions are not compatible with field conditions where soil moisture distribution is always non-uniform due to the continuous wetting/drying processes induced by varying atmospheric conditions. In other words, the mechanical behavior of soil in field must be depth and time dependent. On the other hand, if the temporal–spatial evolution of soil strength during infiltration and evaporation is well known, the soil geotechnical response to rainfall and drought can be evaluated and predicted. It is therefore of primary importance to find or develop proper test methodologies for examining soil strength profile under dynamic water content conditions. In this regard, the cone penetration test (CPT) is regarded as an easy, rapid and relatively economical field test method to investigate the mechanical behavior of soils (Shin and Kim, 2011). Nevertheless, the equipment used is of large size and thus cannot be used in laboratorial testing.

In this investigation, a micro-penetrometer was used to characterize the temporal–spatial evolution of soil strength during W–D cycles. A series of penetration tests were conducted during each drying path. The obtained results allowed the effect of W–D cycles on soil strength profile to be analyzed.

2. Materials and methods

2.1. Materials

The tested soil was collected with spade from Nanjing area, China, in a depth about 0.5–1 m (water table is about −3 m). It is widely distributed in the middle and lower reaches of Yangtze River, and is a very important foundation soil involved in numerous construction projects. In some regions, the thickness of the tested soil layer is larger than 60 m. Its physical properties are summarized in Table 1. According to the USCS classification (ASTM, 2006a), it is a low plasticity clay soil (CL). The clay fraction is dominated by illite and interstratified illite-smectite (Liu and Lv, 1996).

Table 1
Physical properties of the used soils.

Soil properties	Values
Specific gravity	2.73
Consistency limit	
Liquid limit (%)	36.5
Plastic limit (%)	19.5
Plasticity index (%)	17.0
USCS classification	CL
Compaction study	
Optimum moisture content (%)	16.5
Maximum dry density (Mg/m^3)	1.7
Grain size analysis	
Sand (%)	2
Silt (%)	76
Clay (%)	22
Uniformity coefficient	18
Shrinkage limit (%)	8.3

Note: CL, low-plasticity clay; USCS, Unified Soil Classification System (ASTM, 2006a).

2.2. Apparatus

In order to quantitatively characterize the evolution of soil strength profile during W–D cycles, a specific micro-penetrometer equipment was used (Liu et al., 2006; Gu et al., 2014), as illustrated in Fig. 1. It mainly consists of three parts: (i) load/displacement controlling and measuring system (control box, control panel, load transducer and displacement transducer), (ii) platen positioning system (platen and position adjuster), and (iii) data collecting system (data logger and computer). The load frame was driven by a motor that can apply constant displacement rate during the penetration test. The soil sample with the container was placed on the platen. A penetration probe was connected to the load transducer (with a capacity of 100 N to an accuracy of 0.01 N), and fixed on the center of the crossbeam of the load frame. A displacement transducer with a capacity of 50 mm (accuracy of 0.01 mm) was mounted on the platen. Both the load transducer and displacement transducer were calibrated, as indicated in Gu et al. (2014).

In order to reduce the side friction between the micro-penetrometer and the soil matrix, also considering both the load capacity and the tested soil specimen size, a special mini-probe with an enlarged conical head was designed (Fig. 2). The probe has a length of 60 mm. The cone at the probe head has an apex angle of 60°, and the base diameter is 2.0 mm which is slightly larger than the rod (1.5 mm in diameter). The stiffness of the probe was improved by quenching treatment to reach the requirements of the penetration test. During penetration, the force (N) measured by the load transducer corresponds to the tip resistance. The measured displacement corresponds to the penetration depth (d_p). Generally, when the probe penetrates into a soil vertically at a constant rate, the higher the soil strength, the greater the measured penetration resistance (R_p). The resistance of soil matrix can therefore be considered as an indicator of strength (Liu et al., 2006; Gu et al., 2014). According to the obtained penetration resistance and displacement, the penetration curve (R_p versus d_p) can be plotted, and the variation of strength along penetration depth is characterized.

2.3. Preparation of specimens

The collected soil samples were air-dried, crushed and passed through 2 mm sieve. The required mass of soil powder was mixed with deionized water by hand to prepare saturated and homogeneous slurry with an initial water content of 50%, which is about 1.5 times the liquid limit (Table 1). A desired quantity of slurry was poured into a stainless steel container, which are 105 mm in height and 99.2 mm in inner diameter, as schematically shown in Fig. 3 (a). Three long fixing bars were used to fix the baseplate. The container with slurry was placed on a vibration (with amplitude of 0.3 mm and frequency of 50 Hz) device for 5 min to remove entrapped air bubbles. Afterwards, the container was sealed with plastic membrane for at least 3 days to allow slurry deposition. The final settled slurry thickness was about 60 mm. In this investigation, the uniformity of the prepared slurry was checked and ensured by analyzing the grain size distribution of