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

De-Yin Wang, Chao-Sheng Tang, Yu-Jun Cui, Bin Shi, Jian Li

School of Earth Sciences and Engineering, Nanjing University, 163 Xianlin Road, Nanjing 210093, China
Laboratoire Navier-CERME, 6 et 8, avenue Blaise Pascal, Cité Descartes, Champs-sur-Marne, 77455, Marne-la-Vallée cedex 2, France

ABSTRACT

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.

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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 Masnou, 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 Masnou, 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...
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 homogeneous 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 laboratory 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).

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

Table 1

<table>
<thead>
<tr>
<th>Soil properties</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific gravity</td>
<td>2.73</td>
</tr>
<tr>
<td>Consistency limit</td>
<td>36.5</td>
</tr>
<tr>
<td>Liquid limit (%)</td>
<td></td>
</tr>
<tr>
<td>Plastic limit (%)</td>
<td>19.5</td>
</tr>
<tr>
<td>Plasticity index (%)</td>
<td>17.0</td>
</tr>
<tr>
<td>USCS classification</td>
<td>CL</td>
</tr>
<tr>
<td>Compaction study</td>
<td></td>
</tr>
<tr>
<td>Optimum moisture content (%)</td>
<td>16.5</td>
</tr>
<tr>
<td>Maximum dry density (Mg/m³)</td>
<td>1.7</td>
</tr>
<tr>
<td>Grain size analysis</td>
<td></td>
</tr>
<tr>
<td>Sand (%)</td>
<td>2</td>
</tr>
<tr>
<td>Silt (%)</td>
<td>76</td>
</tr>
<tr>
<td>Clay (%)</td>
<td>22</td>
</tr>
<tr>
<td>Uniformity coefficient (%)</td>
<td>18</td>
</tr>
<tr>
<td>Shrinkage limit (%)</td>
<td>8.3</td>
</tr>
</tbody>
</table>

Note: CL, low-plasticity clay; USCS, Unified Soil Classification System (ASTM, 2006a).
the samples taken from the top, middle and bottom layer. Because one specimen is not enough to run all the penetration tests, two identical specimens were therefore prepared following this protocol.

2.4. Test procedures

After the specimens were prepared, they were subjected to three W–D cycles. As mentioned above, drought can result in soil cracking and significant damage to infrastructures, while the mechanical response of soil to drought has not received the deserved concern when compared with that to rainfall. In the present investigation, as the first step, the penetration test was only performed at each drying path. The

![Fig. 1. Schematic drawing of the micro-penetrometer equipment.](image1)

![Penetration load](image2)

![Tip resistance](image3)

![Fig. 2. Schematic drawing of probe penetration process.](image4)

![Fig. 3. Schematic drawing of the specimen container and the porous metal cover. (a) Profile of the container. (b) Top view of the metal cover.](image5)
first drying path started from the initial slurry state. The specimens were exposed to ambient condition (temperature is 22 ± 2 °C and relative humidity is 55 ± 5%) and moved to the platen of load frame for performing penetration test at different time intervals corresponding to different water contents. The test ended when the penetration resistance reached the maximum capacity of the load transducer (100 N). However, the specimens were still subjected to drying until the residual water content was reached. During drying, if the mass change of the specimen is less than 0.1 g in four hours, the residual water content was assumed to be reached. It should be noted that, due to the limitation of the measurement capacity of the load transducer, the penetration tests ended before the specimens reached the residual water content. The subsequent wetting path was followed by adding deionized water into the container. Water was carefully sprayed on specimen surface until the initial water content was reached (about 50%, corresponding to 1.5 times the liquid limit). The container was also sealed with plastic membrane to prevent moisture loss by evaporation. Seven days were allowed for this saturation process. Then, the specimens were exposed to ambient condition and underwent penetration tests again. By repeating the above procedure, a total of three W-D cycles were applied to each specimen.

It should be noted that, during the penetration test, a porous metal cover of about 1 mm thick (Fig. 3(b)) was placed on the top of the specimen to prevent moisture evaporation. In the metal cover, small holes of 3 mm in diameter were drilled for positioning the penetration tests. The penetration positions were carefully selected and marked in the central area of the specimens (about 15–20 mm far away from the boundary) to reduce the boundary effect. About 10–13 penetration tests were performed one after another during each drying path. The distance between each neighboring penetration point was kept 20 mm or larger, which is 10 times larger than the diameter of the penetration cone (i.e. 2 mm). After performing a series of verification tests this distance was proved to be large enough to eliminate any interference between the penetration tests. In order to avoid the probe penetrating in the same hole of the last drying path, the porous metal cover was rotated slightly by about 20 degree for the subsequent drying path. Moreover, only one hole in the top cover was opened for each penetration test, the others being sealed by adhesive tape to reduce moisture evaporation. The penetration rate was fixed at 5 mm/min according to Gu et al. (2014). After each penetration, the mass of specimen was determined by a balance to an accuracy of 0.01 g. The value was used to back-calculate the average water content (w.), and describe the drying process of the specimen. At the end of the third drying path, small soil samples were taken at different depths of each specimen, i.e. 0–5, 5–10, 10–15, 15–20, 20–25, 25–30, 30–35 and 35–40 mm, to determine the water content profile by oven drying at 110 °C (ASTM, 2006).

3. Results

3.1. The first drying path

Fig. 4(a) shows the typical penetration curves (penetration resistance Rp with penetration depth dp) at different wa values during the first drying path. All the curves show similar pattern at the initial stage of the test; the Rp increases with increasing dp before a peak value is reached. Further examination of the results in Fig. 4(a) shows that the critical penetration depth corresponding to the peak Rp generally falls in the range of 2.0–3.0 mm, and increases slightly with the decrease of wa. Apparently, it is little higher than the height (1.73 mm) of the conical probe head. This phenomenon seems more pronounced at lower water contents.

For simplicity and clarity, only the penetration data after dp ≥ 5 mm are plotted for further analysis, as shown in Fig. 4(b). It can be seen that the overall Rp is quite small in the relatively high wa range (i.e. 29.75–19.79%). The Rp increases slightly from about 2 to 12 N as the wa decreases from 29.75% to 19.79%, and the Rp generally remains roughly constant (or more exactly slightly decrease) with increasing dp. However, as wa reaches the relatively low range (16.61–11.64%), the penetration curves are different from that observed in the high wa range. The Rp increases rapidly at shallow depth (Fig. 4(a)) and thereafter decreases exponentially with increasing dp (Fig. 4(b)). For instance, at 5 mm depth, the Rp increases by 342% from approximately 19 to 84 N as wa decreases from 16.61 to 11.64%. This suggests that drying results in not only significant increase in soil strength but also the increase of soil strength heterogeneity in profile. The strength in upper soil layer is higher than that in lower soil layer.

Fig. 5 shows the development of Rp at different depths (5, 10, 15, 20, 25, 35 and 40 mm) with the decrease of wa. When wa is higher than 19.79%, the Rp at different depths are almost the same even though wa decreases by about 10%. During this drying period, the overall Rp in profile increases slightly, and the corresponding increase rate (defined as increment of Rp induced by unit decrease of wa – 1%) is approximately 0.7 N/%. When wa is lower than 19.79%, the Rp at shallow depths (5 and 10 mm) starts to increase rapidly first. When wa reaches 16.61%, the Rp at 15 mm starts to increase rapidly. However, the Rp at other deeper depths (dp ≥ 20 mm) generally increases slightly with decreasing wa. It can be also observed that the increase rate of Rp at each depth increases with the decrease of wa. These results suggest that the development of strength in soil profile by drying exhibits obvious delayed effect with increasing depth.

![Fig. 4. The typical penetration curves during the first drying path. (a) For 0 ≤ dp ≤ 35 mm. (b) For 5 ≤ dp ≤ 35 mm.](image_url)
3.2. The second drying path

After the first drying path was finished, the specimens were fully saturated and subjected to a second drying and penetration test. The obtained penetration curves at different \( w_a \) values are shown in Fig. 6 (a) for the whole penetration depth, and Fig. 6 (b) for \( d_p \geq 5 \) mm. The patterns of penetration curves are similar to those of the first drying path (Fig. 4). It can also be observed that, in the relatively high \( w_a \) range (29.51–83.77%), the overall \( R_p \) is relatively small (about 2–10 N) and remains constant. Upon further drying, the \( R_p \) at shallow depth starts to increase rapidly. For instance, as \( w_a \) decreases from 16.74 to 8.30%, the \( R_p \) at 5 mm depth increases from 12.4 to 81.3 N. The \( R_p \) also decreases exponentially with increasing \( d_p \) (Fig. 6 (b)).

Fig. 7 shows the development of \( R_p \) at different depths (5, 10, 15, 20, 25, 35 and 40 mm) with decreasing \( w_a \). When \( w_a \) is higher than 21.03%, the \( R_p \) at different depths are almost the same. The effect of drying on strength profile is then negligible. The \( R_p \) at 5 mm depth starts to increase rapidly. As \( w_a \) decreases to 16.74 and 10.16%, obvious increase of \( R_p \) can be observed at 10 and 15 mm depths. The \( R_p \) at other deeper depths (\( d_p \geq 20 \) mm) generally increases slightly. This is consistent with the observation of the first drying path (Fig. 5).

3.3. The third drying path

The obtained typical penetration curves during the third drying path are shown in Fig. 8 (a) for the whole penetration depth, and in Fig. 8 (b) for \( d_p \geq 5 \) mm. Unlike the penetration curves obtained from the first and second drying paths, the penetration curves during the third drying path show some fluctuations. Moreover, some curves show multi-peak pattern instead of mono-peak pattern, especially at low \( w_a \) values. For instance, at \( w_a = 9.33\% \), the \( R_p \) reaches the first peak at \( d_p = 3.1 \) mm; after that it decreases and increases to the second peak at \( d_p = 9.5 \) mm; finally, it reaches the third peak at \( d_p = 29.1 \) mm (Fig. 8 (a)). This indicates the more pronounced spatial difference of strength in profile after three \( \text{W-D} \) cycles.

During the first and second drying paths, the corresponding critical depth \( d_p \) at the maximum \( R_p \) usually falls in the range of 2.0–3.0 mm (Figs. 4 (a) and 6 (a)). The \( R_p \) generally decreases monotonously with increasing \( d_p \) after 5 mm depth, and the corresponding penetration curves can be best fitted by a declined exponential function (Figs. 4 (b) and 6 (b)). However, during the third drying path, the critical depth \( d_p \) shifts rightward to larger values (2.5–9.5 mm), as shown in Fig. 8 (a), the largest value of \( d_p \) (9.5 mm) being at \( w_a = 9.33\% \).

Fig. 9 shows the development of \( R_p \) at the specific depths (5, 10, 15, 20, 25, 35 and 40 mm) with decreasing \( w_a \). Similar observation can be made as in the first and second drying paths. When \( w_a \) is higher than 21.12%, the effect of drying on the development of strength profile is low and negligible. After that, the \( R_p \) at \( d_p = 5 \) mm starts to increase. As \( w_a \) reaches 17.72 and 14.54%, the \( R_p \) values at \( d_p = 5, 10 \) and 15 mm start to increase rapidly, with evident delayed effect. In particular, unlike in the former two drying paths, the \( R_p \) at 5 mm depth does not
increase monotonously with further decrease of $w_a$. It reaches a peak value of 43.9 N at $w_a = 11.47\%$, and then decreases to 39.1 N at $w_a = 9.33\%$.

At the end of the third drying path, the actual water content was measured at 5 mm spacing and presented in Fig. 10, the value of $w_a$ being 9.33\%. The corresponding penetration curve is also plotted. The water content generally increases monotonously over depth as expected, while the corresponding penetration curve shows significant fluctuation and apparently has no direct connection with the variation of water content.

3.4. Comparison of the results

In order to better understand the effect of W–D cycles on the soil strength development during drying, the penetration curves at similar $w_a$ for each drying path are shown in Fig. 11 (a) for $w_a$ about 21.0\%, and in Fig. 11 (b) for $w_a$ about 14.5\%. It is observed that the overall $R_p$ and the maximum $R_p$ generally decrease with increasing W–D cycles. For instance, at $w_a = 21.0$ and 14.5\%, the maximum $R_p$ during the third drying path decreased by 72.7\% and 72.3\% respectively as compared with the values in the first drying path. Moreover, the fluctuation of $R_p$ is intensified after the third W–D cycle.

In addition to the average water content, another parameter namely the average penetration resistance $R_{ap}$ was employed to describe the evolution of soil strength during drying. The $R_{ap}$ is defined as the ratio of the area under the penetration curve to the penetration depth. Based on the penetration curves shown in Figs. 4, 6 and 8, the $R_{ap}$ for each $w_a$ can be determined. Fig. 12 shows the variation of $R_{ap}$ with decreasing $w_a$ during the three drying paths. The $R_{ap}$ generally increases exponentially with decreasing $w_a$. At a given $w_a$, the $R_{ap}$ during the former drying path is always higher than that during the subsequent drying paths.

4. Discussion

4.1. The development of strength profile during drying path

As observed in Figs. 4, 6 and 8, at given water content, the soil strength decreases exponentially with increasing depth. This is mainly due to the suction gradient induced in soil during drying. For an initially saturated soil, evaporation generally takes place in three stages (Fig. 13), and starts from the soil surface (Hillel, 1982). In stage I (Fig. 13 (a)), soil is fully saturated. The moisture in deeper soil layers is drawn to the surface for maintaining the evaporation by means of capillary forces which form capillary water columns passing through the air/water menisci. When the air-entry value is reached, air bubbles enter, and the top layer changes from saturated to unsaturated state. The evaporation process transits to stage II (Fig. 13 (b)). After that, suction in the top unsaturated zone tends to be very sensitive to further
The degree of saturation, and the deep pore water is still drawn to the below the evaporation surface, soil is usually saturated or with high water content. With continuous drying, the top unsaturated zone is enlarged, and pushes the evaporation surface deeper. Below the evaporation surface, soil is usually saturated or with high degree of saturation, and the deep pore water is still drawn to the evaporation surface by capillary force. Above the evaporation surface, soil is unsaturated and the evaporation process is dominated by vapor diffusion. Because the pore water that is closer to the soil surface has shorter transfer distance to the ambient environment, it evaporates faster than that in deeper pores. As a result, significant water content gradient as well as suction gradient is established in the upper unsaturated zone. Indeed, Song et al. (2014) performed evaporation test using an environmental chamber and measured suction during drying, their results indicated that suction decreases exponentially with increasing depth. In addition, the measured peak penetration resistance in the near surface zone and the calculated average penetration resistance increase with the decrease of average water content. This phenomenon can also be attributed to the increase of suction in the soil due to drying. With further drying, when the vapor pressure inside soil pore spaces is close to that in the ambient air, the evaporation process transits to stage III (Fig. 13(c)) and the corresponding evaporation rate is near zero. Finally, the residual water content of soil is reached. It is found that, before the average water content $w_a$ reaches a critical value, the strength in profile is generally similar and slightly influenced by the decreasing water content. Based on the results shown in Figs. 5, 7 and 9, this critical value of $w_a$ is determined as about 20 ± 1%. By referring to the above-mentioned evaporation process, it can be deduced that the observed critical average water content is probably related to the soil air-entry value. Before the air-entry value is reached, the soil is saturated, and the moisture distribution is almost uniform, the effect of evaporation on soil suction being insignificant. After the critical value of $w_a$ is reached, the penetration resistance in the surface layer starts to increase rapidly. This is because the surface layer becomes unsaturated, and suction increases rapidly even though the water content decreases slightly. With further drying, the evaporation surface moves down gradually, explaining the observed delayed effect of strength profile. Therefore, according to the penetration results, it is possible to evaluate the development of unsaturated zone in profile, or to assess the evolution of the influence depth of drying. The development of $R_p$ shown in Figs. 5, 7 and 9 suggests that the variation of soil strength at deeper depths ($d_p ≥ 20$ mm) is insignificant for each drying path. It can be deduced that the maximum influence depth of drying is almost limited to 20 mm for the tested specimens. Note that if accurate relationship among penetration resistance, water content and suction is available, the introduced penetration test method would be an economic and rapid way to detect soil mechanical response to climate changes, especially during drought periods. In addition to the contribution of suction, volumetric shrinkage would be another important factor affecting the development of strength during drying. Because clayey soil was tested, volumetric shrinkage must occur during drying, resulting in denser fabric. The number of particle contacts in unit volume therefore increases with decreasing water content, and the strength increases.

4.2. The effect of $W-D$ cycles on strength profile

It is observed that the soil strength profile is significantly influenced by the $W-D$ cycles. For the initially saturated specimens, the overall strength at given water content decreases with increasing $W-D$ cycles, as shown in Figs. 11 and 12. One of the possible reasons is that the soil water retention capacity is decreased after the specimens undergo multiple $W-D$ cycles. Goh et al. (2014) investigated the $W-D$ cycles on soil water retention curve (SWRC) at zero confining pressure, and they found that, at given water content, the soil suction in the drying path is decreasing with the $W-D$ cycles. Another reason may be the soil texture alteration or the structure rearrangement during $W-D$ cycles. When a clayey soil is subjected to wetting, the active clay minerals may adsorb water and swell. Generally, there are two levels of swelling: interlayer swelling at the microscopic scale and bulk volume increase at the macroscopic scale (Likos and Lu, 2006). The interlayer swelling is generally irreversible when the soil is
subjected to subsequent drying. However, the bulk volume increase is generally featured with irreversibility and hysteresis. Many researchers found that accumulated irreversible swelling or volume increase occurred under the effect of W–D cycles (Basma et al., 1996; Cui et al., 2002; Wang et al., 2008; Tripathy et al., 2009; Nowamooz and Masrouri, 2009; Chen and Ng, 2013).

Furthermore, W–D cycles can create larger pores in soil. Sartori et al. (1985) found a strong increase in the intra-aggregate porosity after some W–D cycles for a clayey soil. Pires et al. (2008) investigated the changes in soil structure induced by W–D cycles, and also found that the total pore area increased significantly after repeated W–D cycles, especially for the large pores. Zemenu et al. (2009) performed scanning electron microscopy (SEM) and mercury intrusion porosimetry (MIP) tests on a clayey soil which was subjected to multiple W–D cycles. The results indicated that W–D cycles cause significant changes of soil structure — the pore volume and the average diameter of pores increase with W–D cycles.

W–D cycles can also result in crack development in soil. Tang et al. (2011) investigated the effect of W–D cycles on the desiccation cracking behavior of a clay slurry. They found that the extent of soil cracking was significantly enhanced by increasing W–D cycles. They also found that, after the first W–D cycle, the subsequent W–D cycles change the homogenous slurry structure to an aggregated-structure. A large amount of macroscopic inter-aggregate pores were created, significantly increasing the soil heterogeneity. Lu et al. (2002) studied the effect of W–D cycles on soil microstructure through CT tests. They found that W–D cycles gave rise to the development of soil cracks. The number and connectivity of cracks increased with increasing W–D cycles.

With the increase of total bulk volume, the creation of large pores and the development of cracks by the W–D cycles, the soil overall density and particle contacts per unit volume decrease. Consequently, the overall strength tends to decrease (Figs. 11 and 12). The presence of large pores or possible cracks in soil creates weak zones in soil and significantly intensifies the spatial heterogeneity of structure. This explains the observed fluctuation of penetration curves during the third drying path (Figs. 8 and 11). The significance of these observations is that the penetration curves can be used to rapidly detect soil inner structure defects with minimum disturbance. It can be also concluded that the soil strength is not only conditioned by the water content/suction distribution, but also significantly linked to microstructure features, as shown in Fig. 10.

In geotechnical practice, the measured penetration resistance is usually used to evaluate the in-situ overconsolidation ratio (OCR) of soil (Mayne and Kemper, 1988; Jian et al., 2005). Generally, for a given soil, the penetration resistance increases with increasing OCR. For the tested soil specimens in this study, the increase of suction during drying path could result in the increase of OCR. According to the measured water content profile shown in Fig. 10, it can be assumed that OCR decreases monotonously over depth as well as the penetration resistance. However, this is not the case if the soil has undergone multiple W–D cycles. As can be seen in Fig. 10, the measured penetration resistance profile shows significant fluctuation along the depth, indicating that the correlations between penetration resistance and OCR is not unique even for a given soil. It confirms again that the soil mechanical behavior is conditioned by both the water content/suction and fabric features.

4.3. The critical penetration depth

For all the penetration curves, the penetration resistance increases monotonously with increased $d_p$ at the initial stage of the test. This phenomenon can be attributed to the used conical probe head (Fig. 2). Before the conical probe head was fully penetrated into the soil, the contact area between the probe and the soil gradually increased. However, it is observed that the critical penetration depth that corresponds to the maximum penetration resistance is higher than the height of the cone head (Fig. 2), and generally increases with decreasing water content. It means that, even though the cone head fully penetrates into the soil and has the maximum contact area with the soil, the penetration resistance does not still reach the maximum value. In other words, upon drying, the maximum strength moves down to deeper locations and this is in conflict with the suction development as discussed above. Usually, the suction of upper soil layer should be always higher...
than that of lower soil layer, because the water content of upper layer is always lower before the drying comes to the end. Therefore, in theory, the critical penetration depth should be lower than the height of the cone head. Actually, the observed intriguing phenomenon may be interpreted by referring to the typical shear failure modes of shallow foundation soil under footing (Chen and Abu-Farsakh, 2015; Lambe and Whitman, 1969). At high water content condition, the specimens are loose and soft, and present high compressibility. During penetration, punching shear failure of upper soil layer may occur. The soil under the cone head is compressed with large strain, resulting in the increase of the strength of lower soil. For given diameter of the probe, the compression zone increases with increasing contact area between cone head and soil. After the cone head is fully penetrated into the soil, the compression zone may still develop until the critical penetration depth is reached, where the penetration resistance reaches the maximum value.

With water content loss, the developed suction leads to soil volume shrinkage, increasing the density and the stiffness, while decreasing the compressibility. During penetration, generally shear failure may occur at shallow depth around the probe. Consequently, the maximum penetration resistance can be only obtained at a deeper position, which is usually several times of the cone head height/diameter for stiff soils (Chen and Abu-Farsakh, 2015; Lambe and Whitman, 1969), as shown in Figs. 4, 6 and 8.

It is also found that the critical penetration depth increases with increasing W–D cycles, and this phenomenon is more pronounced after the third cycle. This is because the W–D cycles result in irreversible volume change and structure rearrangement as discussed above. The reduction of overall density and the presence of large pores or cracks can significantly increase the soil compressibility.

4.4. Effect of water content/W–D cycles on the bearing capacity of pile

It is well known that the cone penetration test “CPT” is one of the most commonly used field investigation technique for evaluating the geotechnical properties of soils. In particular, thanks to the similarity between cone penetrometer and pile, the measured penetration resistance is widely applied to the estimation of the bearing capacity of pile. In the past several decades, numerous empirical relationships between cone penetration resistance and pile bearing capacity were proposed (Eslami and Fellenius, 1997; Cai et al., 2009). However, none of them took into account the effect of water content or W–D cycles. As discussed above, the penetration resistance measured by the micro-penetrometer reflects the mechanical behavior of soil along depth. The obtained results may therefore be useful for assessing the effect of water content/W–D cycles on bearing capacity of pile.

As shown in Figs. 4, 6, 8 and 12, the penetration resistance depends significantly on soil water content, and generally increases exponentially with the decrease of water content. Therefore, if the variation of soil moisture is not properly accounted, the determined pile bearing capacity based on one in-situ CPT data would be overestimated or underestimated. More importantly, if the field considered underwent a long-term heavy drought before the CPT tests, the determined pile bearing capacity would be significantly overestimated. Consequently, large settlement of foundation even damage of building may occur during the subsequent wet weather. In arid and semi-arid regions where the field is usually composed of thick unsaturated soil, it is recommended to consider soil water content change induced by extreme climate events (i.e. heavy drought and precipitation) as well as its effect on the bearing capacity of foundation, especially shallow foundation.

Based on the determined average penetration resistance $R_{ap}$ and the base area ($0.03 \text{ cm}^2$) of the used cone head (Fig. 2), the average unit cone tip resistance ($q_c$) is calculated for each drying path, and the results are presented in Fig. 14. Taking the first drying path as an example, as $w_a$ decreases from 29.75 to 11.64%, $q_c$ increases dramatically by 23.5 times from 0.47 to 11.05 MPa. This means that per unit change of water content would result in about 0.6 MPa variation of the unit cone tip resistance. Based on the best fitting curve of the first drying path, the relationship between $q_c$ and $w_a$ can be derived, as follows:

$$q_c = 107.12 \times e^{-0.22w_a} + 0.37.$$ (1)

It should be noted that the above equation cannot be directly used to estimate the end-bearing capacity of pile, because the employed micro-penetrometer is not a real CPT device, and cannot also be simply considered as a mini-CPT (MCPT) device. We assume there must be significant scale effects as compared with the standard CPT test. Furthermore, the relationship is deduced from the average penetration resistance and characterized by the average water content. Comprehensive calibration tests should be performed to refine the relationship between $q_c$ and CPT cone resistance. Systematic theoretical work on the mechanical interaction between the probe and soil particle and sufficient field tests are also required before the application of the proposed micro-penetrometer to practice.

In addition to water content, the W–D cycle is another factor affecting pile bearing capacity. From the results shown in Fig. 14, it can be seen that the pile bearing capacity decreases with increasing W–D cycles. Based on the fitting equations of the three drying paths, the decrease of average unit cone tip resistance $\Delta q_c$ from the first to the second drying path $\Delta q_{c, 1-2}$, and from the second to the third drying path $\Delta q_{c, 2-3}$ at different given water contents are calculated and shown in Fig. 15. It can be seen that, with increasing W–D cycles, the reduction of unit cone tip resistance is more pronounced at lower water content. On the whole, $\Delta q_c$ increases exponentially with decreasing water content. The reduction of $q_c$ from the first to the second W–D cycle $\Delta q_{c, 1-2}$ is more pronounced than that from the second to the third W–D cycle $\Delta q_{c, 2-3}$. Many researchers studied the effect of W–D cycles on soil shear strength (Liu and Yin, 2010; Yang et al., 2014), and the maximum reduction of cohesion was also usually observed from the first to the second cycle. This is consistent with the results shown in Fig. 15, and can be attributed to the weakening of soil structure (Tang et al., 2011). Moreover, it was found that soil hydro–mechanical behavior generally reaches stabilization after three to five cycles (Basma et al., 1996; Liu and Yin, 2010; Tang and Shi, 2011; Yang et al., 2014).

5. Conclusions

A micro-penetrometer was used to investigate the evolution of the strength profile of a silty clay subjected to multiple W–D cycles. The

![Fig. 14. The relationship between $q_c$ and $w_a$ during each drying path.](image-url)
effects of drying and W–D cycles on soil strength profile were analyzed. The following conclusions can be drawn:

1. The proposed micro-penetration test provides a simple, quick, economic and reliable laboratory method to investigate the soil strength profile. The test shows a potential in evaluating the temporal–spatial evolution of soil strength profile.

2. When the initially saturated soil is subjected to drying, the strength along the profile is uniform and is slightly affected by water evaporation before a relatively low critical water content is reached. After that, the strength generally increases exponentially with the decrease of water content, and decreases exponentially over depth. The observed critical water content is probably related to the air-entry value of soil. Moreover, the mechanical response of the upper soil zone is more sensitive to drying as compared to the deeper soil zone. The drying induced development of strength presents evident delayed effect along the depth.

3. The temporal–spatial evolution of soil strength profile is significantly influenced by the W–D cycles. Generally, the average strength at a given average water content decreases with increasing W–D cycles, and this reduction is more pronounced at lower water contents.

4. During the first two W–D cycles, the penetration resistance versus average water content shows similar behavior and the effect of W–D cycles is small. However, after the specimens are subjected to the third W–D cycle, the penetration resistance with penetration depth shows obvious fluctuation, and the penetration curves change from typical mono-peak pattern to multi-peak pattern. The heterogeneity of strength distribution is significantly intensified after the third W–D cycles. This phenomenon is also more significant at lower water content.

5. The development of strength profile during drying is related to the soil water evaporation process. In addition to suction, the strength profile also significantly depends on soil structure features, i.e. pore sizes, heterogeneous zones and cracks.

It should be noted that the present study provides primary data about soil strength profile and the effect of W–D cycles. The lack of actual water content and suction does not allow more quantitative analysis. In the future work, calibration tests will be performed to establish quantitative relationships among penetration resistance, water content and suction. Some MIP and SEM tests will be also carried out to clarify the microstructure changes.

Acknowledgments

This work was supported by the National Natural Science Foundation of China for Excellent Young Scholars (Grant No. 41322019), National Natural Science Foundation of China (Grant No. 41572246), Key Project of National Natural Science Foundation of China (Grant No. 41230636), and the Fundamental Research Funds for the Central Universities (Grant No. 020614380013). The authors want to address their thanks to the 6 anonymous reviewers for their constructive comments, and Mr. Xiao-Wei Luo at Nanjing University for his help in performing the tests. The authors also wish to acknowledge the support of the European Commission via the Marie Curie IRSES project GREAT-Geotechnical and geological Responses to climate change: Exploring Approaches and Technologies on a world-scale (FP7-PEOPLE-2013–IRSES-612665).

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