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ORIGINAL ARTICLE

Impact of multiple drying–wetting cycles on shear behaviour of an unsaturated compacted clay

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Abstract

Experimental investigations on the impact of multiple drying–wetting cycles on mechanical behaviour of unsaturated soils, particularly on shear behaviour, are limited. Suction-controlled direct shear tests were carried out to investigate the impact of multiple drying–wetting cycles on shear behaviour of an unsaturated compacted clay. One drying–wetting cycle was applied on a soil specimen by increasing its suction to 400 kPa followed by returning its suction to 1 or 200 kPa at constant vertical stress. The experimental results showed that more significant volume contraction occurred during the first drying–wetting cycle as compared with the subsequent drying–wetting cycles. At higher net normal stress (i.e. 200 kPa), a transition from shear-induced contraction to dilation was found. Nevertheless, such transition from contraction to dilation was not observed for the specimens at lower net normal stress (i.e. 50 kPa). The results also showed that amplitude of drying–wetting cycles and vertical stress influences the shear strength. The shear strength increases slightly after the first drying–wetting cycle at lower net normal stress; at higher net normal stress the effect of the first cycle on the shear strength is contrast.

Keywords Suction history · Drying–wetting cycle · Clay · Suction · Hydro-mechanical behaviour · Direct shear test

Introduction

Hydro-mechanical behaviour of an unsaturated soil at a given suction is significantly affected by its recent suction history, i.e. following wetting or drying to reach the given suction, due to hydraulic hysteresis, as revealed by, e.g. Wheeler and Karube (1995), Tamagnini (2004), Gens et al. (2006), Sivakumar et al. (2006), Thu et al. (2006), Ng et al. (2009, 2013), Guan et al. (2010), Zhou and Ng (2014), Liu et al. (2016), He et al. (2017), Li et al. (2017) and Wang et al. (2017). In addition to recent suction history, the number of drying–wetting cycles also influences hydro-mechanical behaviour of unsaturated soils (Ng and Pang 2000; Wheeler et al. 2003).

The effect of multiple drying–wetting cycles on volume change of unsaturated soils has been studied by Pardini et al. (1996), Alshihabi et al. (2002), Estabragh et al. (2015) and Rosenbalm and Zapata (2016). Pardini et al. (1996) found that multiple drying–wetting cycles lead to opening of fissures and hence to an increase in total porosity for a clayey soil derived from a smectite-rich mudrock. The number of pores did not increase after three drying–wetting cycles, indicating that no micro-disintegration of soil material had likely occurred. In contrast, Alshihabi et al. (2002) found that drying–wetting cycles caused contraction first for the compacted Bavent clay and hence expansion with the increasing number of drying–wetting cycles. Test results of Estabragh et al. (2015) show that the swelling–shrinkage during cyclic wetting and drying was reversible after the soil reached the equilibrium condition where the deformations were the same and the relationship between water content and void ratio for cyclic wetting and drying converged to an S-shaped curve. The hysteresis phenomenon diminished gradually with the increase in the number of drying–wetting cycles. The results show that the soil specimens with lower initial water content (on the dry side of optimum) have higher swelling potential than those with higher initial water content (on the wet side of optimum). Irreversible swelling and shrinkage were observed over drying–wetting cycles for soil specimens under different surcharge pressures.

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Reversible deformation was achieved after about four or five drying–wetting cycles when the equilibrium condition was attained. The potential of swelling and shrinkage decreased with the increasing surcharge pressure. The hysteresis phenomenon was observed during the drying–wetting cycles, but after achieving the equilibrium condition it was eliminated. The study by Rosenbalm and Zapata (2016) on two naturally expansive soils shows that swelling or collapse strain and swelling pressure reached equilibrium after four drying–wetting cycles. When the applied stress exceeded 25% of the swelling pressure, both soils exhibited an increase in collapse potential. However, when the applied stress was less than 25% of the swelling pressure, both soils exhibited an increase in swelling potential.

Regarding mechanical behaviour, Nowamooz and Masrouri (2008) observed that the drying–wetting cycles applied to both the micro- and macro-structure significantly influenced the apparent pre-consolidation stress and the elastic compression index values. However, the hydraulic cycles imposed only on the micro- or macro-structure lead to negligible changes in the mechanical parameters of the soil. Tse et al. (2008) carried out laboratory and field research on the hydro-mechanical behaviour of an unsaturated completely decomposed tuff subjected to artificial drying–wetting cycles. It was found that, in laboratory tests, as drying–wetting cycle progressed, the difference in mechanical behaviour, e.g. dilatancy and peak shear strength, of specimens subjected to drying and wetting decreased at a given suction. From a series of suction-controlled isotropic compression tests on the unsaturated Zaoyang clay subjected to various drying–wetting histories, Chen and Ng (2013) found that wetting followed by drying leads to a smaller pre-consolidation stress and down-shifting of the post-yield compression curve at a given suction, whereas a suction history of wetting–drying–wetting shows an opposite effect.

The above studies focus on the deformation behaviour, rather than the shear behaviour of unsaturated soil subjected to multiple drying–wetting cycles. Goh et al. (2014) studied the shear strength characteristics of unsaturated soil under multiple drying–wetting cycles by a series of unsaturated consolidated drained triaxial tests on sand–clay mixtures. The experimental results indicated that the difference between the shear strengths on the drying and wetting paths of the first cycle was more significant than the difference between the shear strengths on the drying and wetting paths of the subsequent cycles. However only one to three drying–wetting cycle(s) was/were applied to the specimens and more drying–wetting cycles should be applied to achieve further understanding on the effect of drying–wetting cycles on hydro-mechanical behaviour of unsaturated soils.

This paper presents the suction-controlled direct shear tests on an unsaturated compacted clay subjected to multiple drying–wetting cycles at vertical stresses of 50 and 200 kPa. One to five cycle(s) was/were applied to the specimens. The underlying mechanisms of multiple drying–wetting cycles on the shear behaviour of the unsaturated clay were investigated.

Table 1 Properties of the clay for testing

Index	Value
Liquid limit	57%
Plastic limit	36%
Plasticity index	21
Maximum dry density	1.36 g/cm^3
Optimum moisture content	32.5%
Specific gravity	2.62

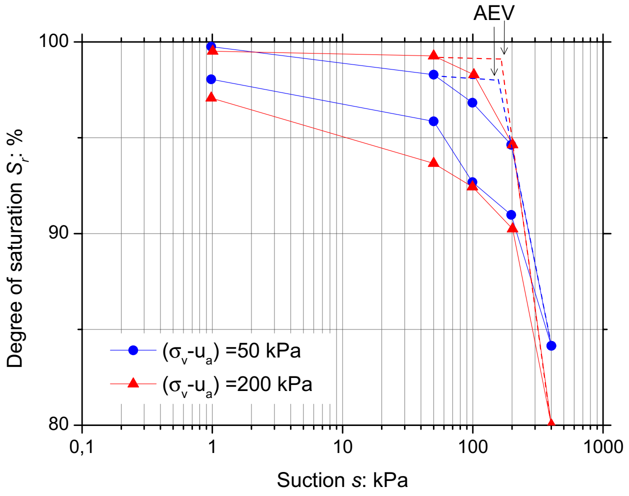


Fig. 1 Water retention curves of the clay

Test material and test methodology

Test material

The soil used in this laboratory study is a fine-grained clay from China. The soil has 8% sand (0.075 mm < grain size < 4.75 mm), 62% silt (0.002 mm < grain size < 0.075 mm) and 30% clay (grain size < 0.002 mm), which is classified as a silty clay according to GB/T 50145-2007 (CNS 2007). The properties of test soil are summarized in Table 1. The water retention curves of a compacted specimen at dry density of 1.20 g/m^3 and at net normal stresses of 50 and 200 kPa are shown in Fig. 1. It can be seen from the figure that its air-entry-value (AEV) is about 130 kPa at net normal stress of 50 kPa and about 160 kPa at net normal stress of 200 kPa. The specimen preparation was performed according to the Chinese standard SL 237–1999 (CSS 1999).

The soil was first put in oven at 105 °C for 12 h. Then, the soil was wetted to a moisture content of 28%. The sample was sealed in a plastic bag for 7 days so that it reached moisture content equilibrium. The soil was compacted using a rammer in three layers, as applying the same number of blows per layer into a cutting ring with 61.8 mm diameter and 20 mm height.

Equipment

A suction-controlled direct shear testing system was set up for this study (Fig. 2). This system was equipped with a loading frame and a gearbox to control the net normal stress, σ_v, and the shear stress, τ, respectively. The pore air pressure, u_a, was controlled in the air chamber. Suction, $s = (u_a - u_w)$, was applied to a specimen by controlling air pressure based on the axis translation principle proposed by Hilf (1956), since the pore water pressure was maintained at the atmospheric pressure. A 500 kPa high air-entry-value (HAEV) ceramic disk was used for this purpose. Both vertical and horizontal displacements were measured by the linear variable displacement transducers (LVDTs). More details could refer to Qiao (2013).

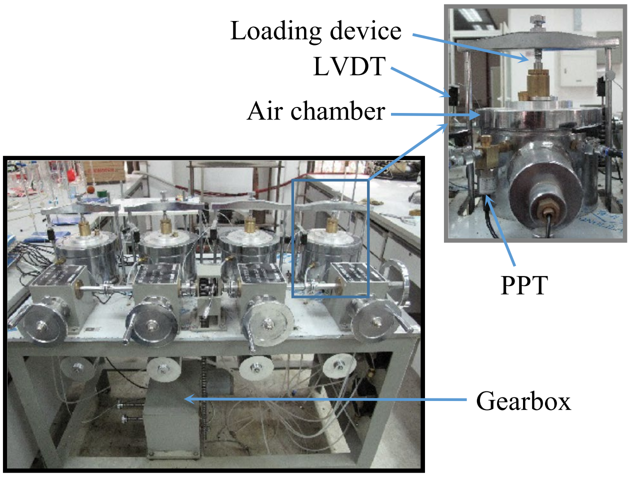


Fig. 2 Schematic diagram of suction-controlled direct shear system for unsaturated soils

Testing program and procedure

As shown in Fig. 3, the initial state of each specimen after compaction is indicated by Point O in ($\sigma_v - u_a$): s plane. Points A, B and C/D denote the initial state in the shear box, equilibrium state under suction of 1 kPa, and the state after consolidation, respectively. Meanwhile, points C and D denote a net normal stress of 50 kPa and 200 kPa, respectively. Each test included three stages prior to shearing, i.e. (1) suction equalization (Path O → A → B), (2) drained consolidation at a constant suction (Path B → C/D) and (3) a cycle of drying (Path C/D → G) and wetting (Path G → C/D for Series 1, Path G → F for Series 2) and subsequent more cycles (if any) (i.e. C/D → G → C/D for Series 1 whereas F → G → F for Series 2). A step-loading approach was adopted to change the suction during drying–wetting cycles. At each step, the applied suction was kept constant until suction equilibrium. After drying–wetting cycles, direct shearing was applied with horizontal displacement at a rate of 0.00196 mm/min. This rate was adopted to limit excess pore-water pressure developed during shearing. After shearing, a 24-h rest period was allowed to ensure full dissipation of excess pore-water pressure throughout the specimen. It was observed that the changes in volume and water content during the rest period were negligible. This indicates that excess pore-water pressure during shearing was negligible and the loading rate used was appropriate.

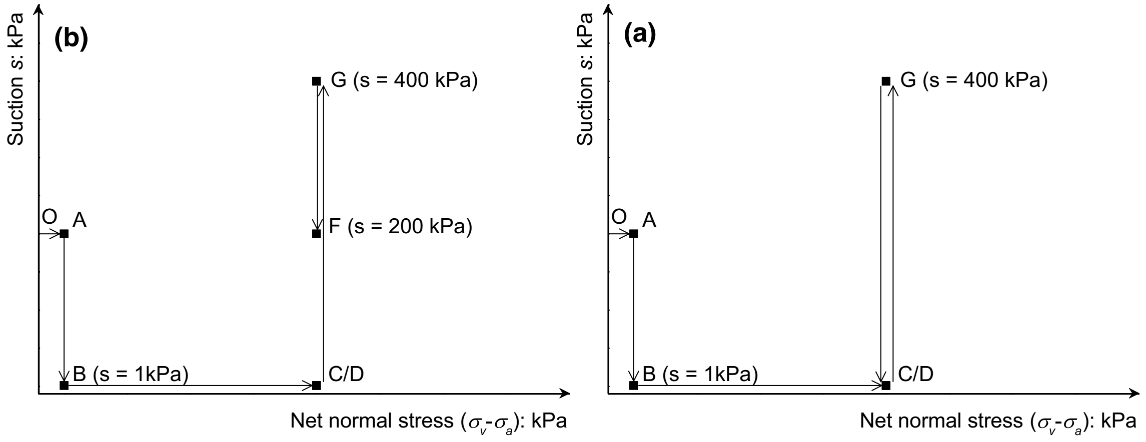


Fig. 3 Stress paths adopted in **a** Series 1 and **b** Series 2

Experimental results and discussion

Volumetric behaviour

Figure 4 shows the variations in void ratio of soil specimens with the number of drying–wetting cycles. For Series 2, the largest volume contraction was caused by the first cycle. However, for Series 1, the largest volume contraction was caused by the second cycle rather than the first cycle. After the second cycle, the volume change is very small. Furthermore, higher vertical stress generally led to a smaller void ratio because it probably resulted in smaller volume of pores among soil particles.

Shear behaviour

Figures 5 and 6 show shear stress (τ), vertical displacement (δ_y) and degree of saturation (S_r) versus horizontal displacement (δ_x) of soil specimens that experienced different numbers of drying–wetting cycles. For Series 1 in Fig. 5a, generally, clear peak shear stress and residual shear stress were observed. It was also shown that peak and residual shear stresses varied with the number of cyclic drying–wetting. A possible reason is that, with the increasing number of cyclic drying–wetting, the specimen would be extensively disintegrated as compared with the first cycle of drying–wetting (Tang et al. 2016). The presence of cracks would create weak zones in soil, but significantly intensify the spatial variability of structure and, thus, led to different shear behaviour of specimens.

Cyclic drying–wetting leads to volume contraction and, thus, the shear strength and the brittleness of the specimen will increase. However, cyclic drying–wetting will also lead to cracks or internal damage (the internal structure is damaged). Moreover, these features can be affected by the amplitude of drying–wetting cycle and vertical stress in different ways. Therefore, the effect of drying–wetting cycles can be different under various conditions.

For Series 2 (Fig. 5a), generally, clear strain-softening behaviour was also found. But the strain-softening behaviour was not obvious for the specimen that experienced one cycle of drying–wetting. It was likely that specimen behaved like a normally consolidated soil. As compared with Series 1 (Fig. 5a), the specimens in Series 2 (Fig. 5a) exhibited more brittle behaviour. This may be caused by the larger volumetric changes, which can be observed from Series 2 in Fig. 5b.

It is clear that peak shear stress increased with the number of cyclic drying–wetting for Series 1 in Fig. 6a. The void ratio after wetting and drying decreased with the number of drying–wetting cycles (Fig. 4), causing decrease in pores and hence more contact points among particles. Consequently, the interparticle contact forces transmitted through the soil skeleton increased. The specimens in Series 2 in Fig. 6a showed more ductile behaviour due to smaller dilation.

Clear shear-induced strain softening was generally observed in Fig. 5b; moreover, the dilations in Series 2 were extremely higher than Series 1. For Series 1 in Fig. 6b, shear-induced contraction was observed for the specimens that experienced 1–3 cycles of drying–wetting. In contrast, when experiencing 4–5 cycles of drying–wetting, the specimens showed clear shear-induced dilation. For Series 2 in Fig. 6b, shear-induced contraction was observed for the specimens that experienced 1–4 cycles of drying–wetting. In contrast, when experiencing five cycles of drying–wetting, the specimens showed clear shear-induced dilation. It was likely that, with the increase of cycle number, the dilatancy of soil may transit from dilation to contraction. This was not reported in previous studies, e.g. Goh et al. (2014). The mechanism will be discussed in the next section.

It can be seen from Series 1 in Fig. 5c, and Series 1 and 2 in Fig. 6c that more drying–wetting cycles resulted

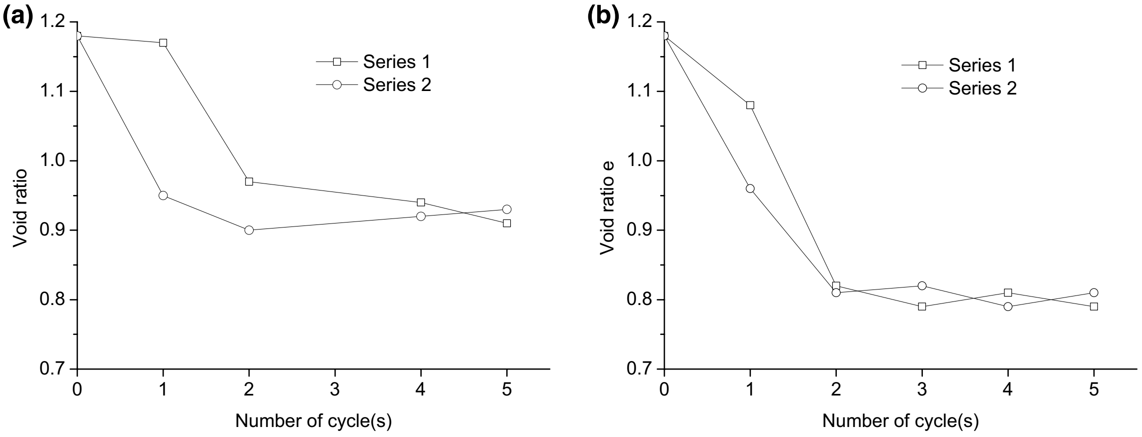
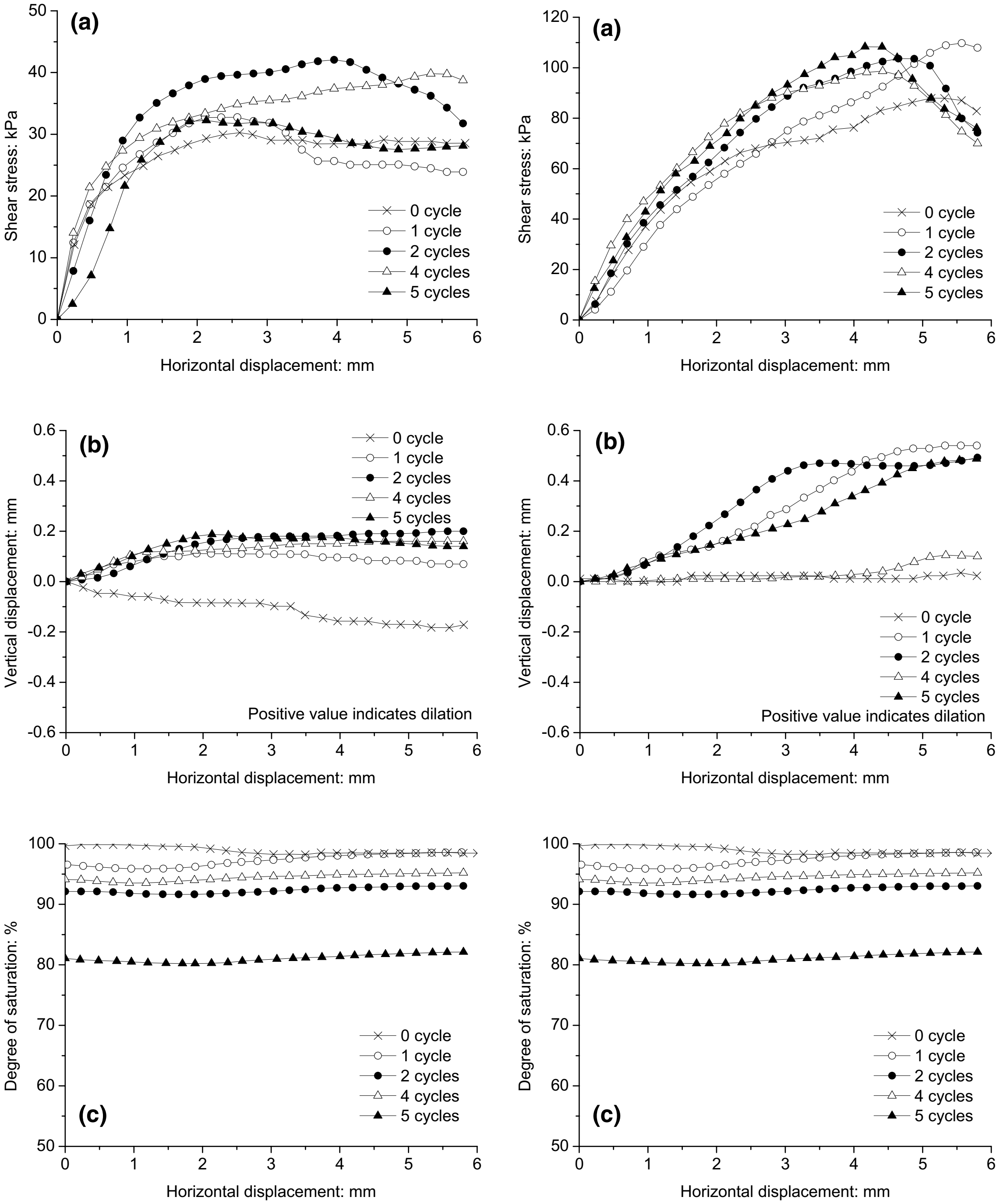


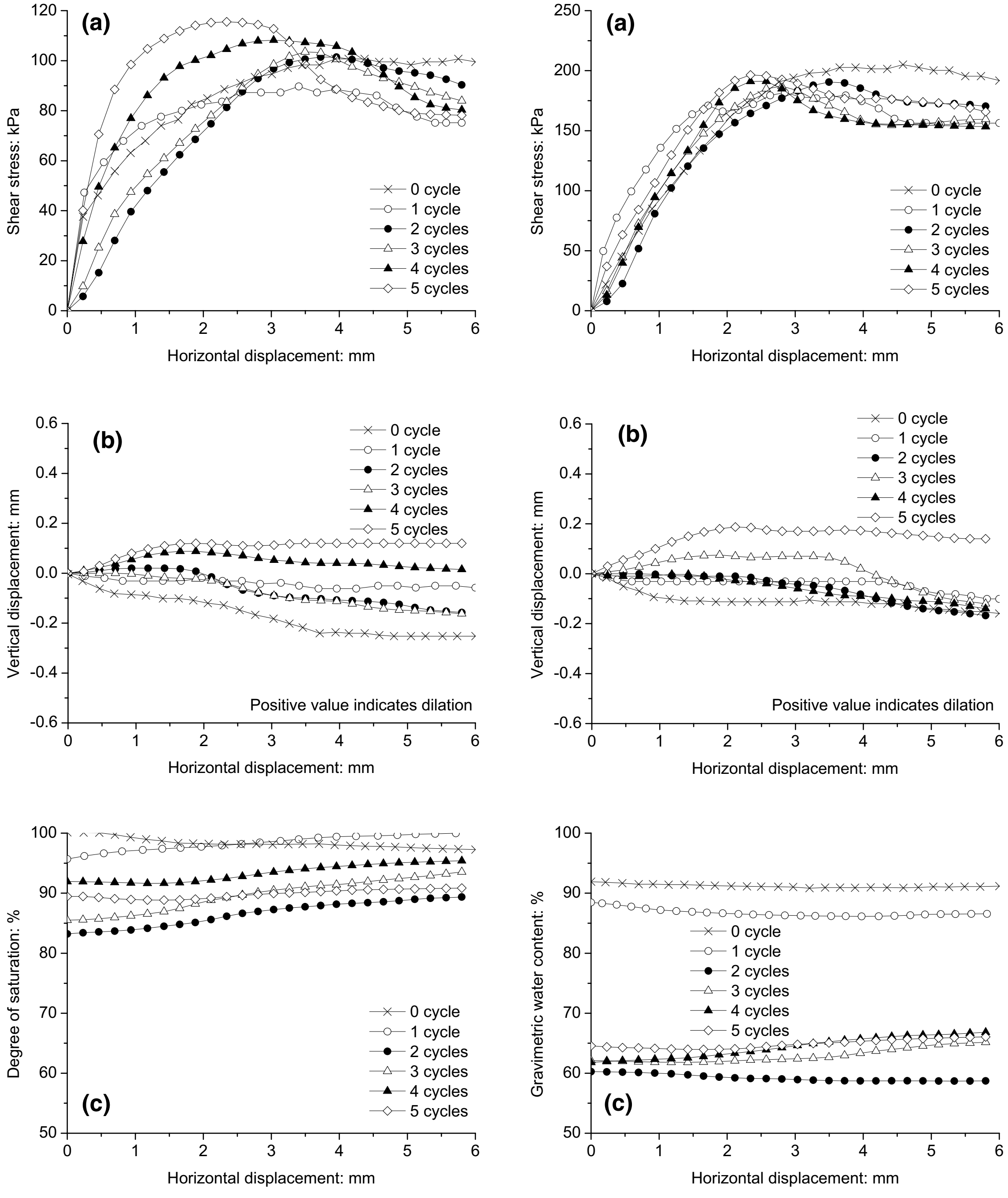
Fig. 4 Variations in void ratio with the increasing number of drying–wetting cycles at **a** $(\sigma_v - u_a) = 50$ kPa and **b** $(\sigma_v - u_a) = 200$ kPa



(i) Series 1 (ii) Series 2

Fig. 5 Shear behaviour after different numbers of drying–wetting cycles at $(\sigma_v - u_a) = 50$ kPa: **a** shear stress, **b** vertical displacement and **c** degree of saturation, versus horizontal displacement

in lower degree of saturation at a given horizontal displacement. In contrast, the degree of saturation of the specimen that experienced one drying–wetting cycle was the lowest for Series 2 in Fig. 5c. The pore volume of specimens with dilation was larger than the specimens with contraction and, hence, the degree of saturation was smaller. The change of degree of saturation is simultaneously influenced by both water content and degree of saturation before shearing and deformation tendency during shearing (Tse et al. 2008). Due to the different degrees of saturation before shearing, the shear behaviour of soil experienced various numbers of drying–wetting cycles



(i) Series 1 (ii) Series 2

Fig. 6 Shear behaviour after different numbers of drying–wetting cycles at $(\sigma_v - u_a) = 200$ kPa: **a** shear stress, **b** vertical displacement and **c** degree of saturation, versus horizontal displacement

may be different. Nevertheless, with increase of drying–wetting cycles, the comparatively large inter-particle air voids may be smaller and soil particles may roll into the interparticle air voids, resulting in a more effective packing pattern. Hence, a net volumetric contraction was observed throughout shearing no matter how many numbers of drying–wetting cycle the specimens experienced. However, the specimens with smaller void ratios prior to shearing might behave more like over-consolidated soil at high net normal stress. Therefore, a volumetric dilation was observed for the specimens that experienced four and five drying–wetting cycles in Series 1 and five drying–wetting cycles in Series 2.

Soil dilatancy

Figures 7 and 8 show the soil dilatancy of the specimens that experienced different numbers of drying–wetting cycles. At low suction ($s = 1$ kPa) and net normal stress ($\sigma_v - \sigma_a = 50$ kPa), the dilative behaviour appeared at the very beginning of shearing, as shown in Fig. 7a. The dilatancy of specimens that experienced more than one drying–wetting cycles was slightly greater than that experienced only one drying–wetting cycle. The reason may be that the specimens that experienced more than one drying–wetting cycles had higher over-consolidation ratios than the specimen that experienced only one drying–wetting cycle (Zhan and Ng 2006) because the void ratios of the specimens that experienced more than one drying–wetting cycles were significantly lower than that of the specimen that experienced only one drying–wetting cycle. Generally, the maximum dilations in Series 2 (Fig. 7b) were larger than Series 1 (Fig. 7a). For Series 1 in Fig. 8, the specimen that experienced one drying–wetting cycle showed fluctuated dilation and contraction during shearing. A clear contraction was observed for the specimens that experienced two and three drying–wetting cycles. Moreover, the value of the peak contraction of specimen after three drying–wetting cycles was larger than that after two drying–wetting cycles. As the number of drying–wetting cycles increases, a clear shear-induced dilation was found at the beginning of shearing. The specimen after five drying–wetting cycles has a larger value of the peak contraction than that after four drying–wetting cycles. This transition was also found for Series 2 in Fig. 8. The specimens experienced one to three drying–wetting cycles showed small contraction. A peak dilation was observed at the beginning of shearing, whereas a peak contraction was observed at the end period of shearing for the specimen experienced four drying–wetting cycles. Significantly, the specimen that experienced five drying–wetting cycles showed an apparent dilation as in Series 1. As the number of drying–wetting cycle increases, a transition from shear-induced contraction to shear dilation was observed. It indicated that the contraction of the specimens that experienced

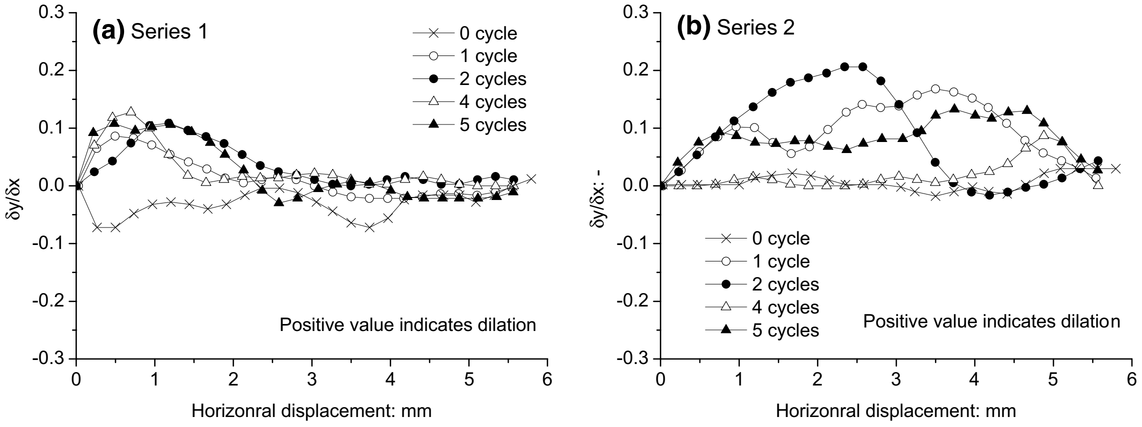


Fig. 7 Shear-induced dilatancy after different numbers of drying–wetting cycles at $(\sigma_v - \sigma_a) = 50$ kPa

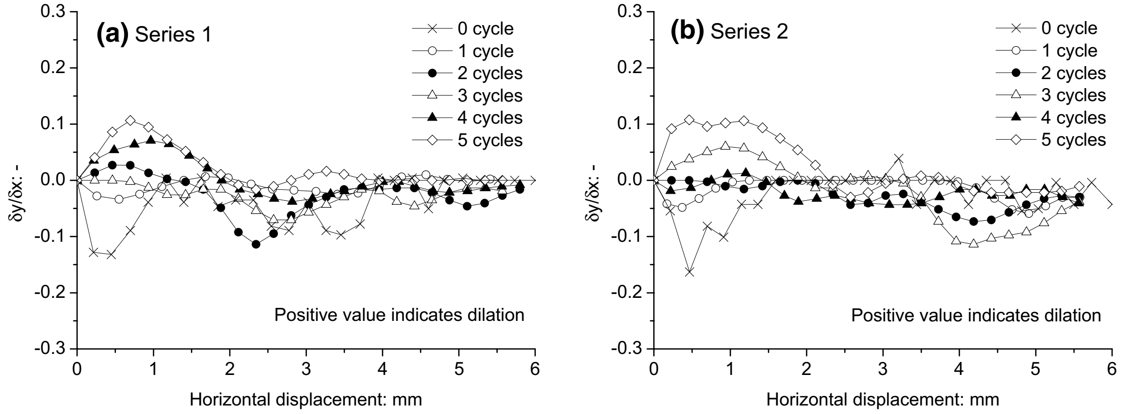


Fig. 8 Shear-induced dilatancy after different numbers of drying–wetting cycles at $(\sigma_v - \sigma_a) = 200$ kPa

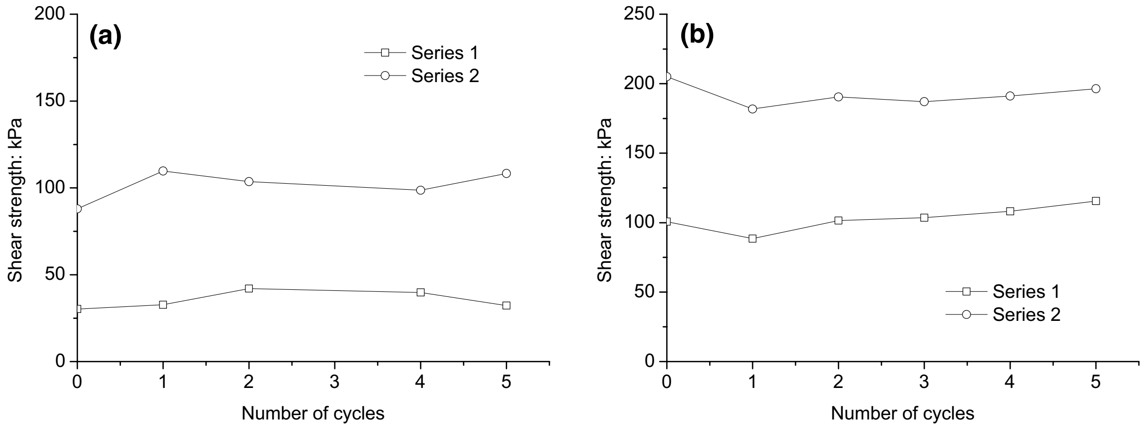


Fig. 9 Shear strength change with the number of drying–wetting cycles: **a** $(\sigma_v - u_a) = 50$ kPa and **b** $(\sigma_v - u_a) = 200$ kPa

one to three or four drying–wetting cycle(s) might be resulted from the effect of the high net normal stress on the movement of soil particles. However, with the increase in over-consolidation ratio induced by the increasing drying–wetting cycles, the constraint effect was significantly reduced; the specimens thus behaved apparently dilative.

Shear strength

Figure 9 shows the shear strengths after different numbers of drying–wetting cycles. At $(\sigma_v - u_a) = 50$ kPa, the shear strength increases slightly after first cycle and varied after subsequent cycles, depending on the number of cycles and the suction. However, at $(\sigma_v - u_a) = 200$ kPa, the shear strength decreased slightly after the first cycle and increased slightly after subsequent cycles. This indicates that the effect of drying–wetting cycles on shear strength depends on the vertical stress. The contribution of suction to the shear strength may be contrast. At $(\sigma_v - u_a) = 200$ kPa, the shear strength increases probably because drying–wetting cycles not only produce damage but also densitify soil specimens. Furthermore, the influences of drying–wetting cycles on the shear behaviour also depend on the amplitude of drying–wetting cycle and vertical stress, the shear behaviour and thus the shear strength will be different after different numbers of drying–wetting cycle and at different vertical stresses.

Conclusions

Two series of suction-controlled direct shear tests were carried out on an unsaturated clay subjected to multiple drying–wetting cycles. The following conclusions may be drawn from the experimental results.

1. The effect of the first drying–wetting cycle has more significant effect than the subsequent drying–wetting cycles on the volumetric change. At low net normal stress (50 kPa), higher suction may lead to more brittle behaviour. On the other hand, high net normal stress leads to more ductile behaviour due to lower even negative volumetric changes.
2. The soil dilatancy can be significantly affected by the number of drying–wetting cycles. At low net normal stress, all the specimens behaved dilative. However, at high net normal stress, a transition from contraction to dilation was found for the specimens as the number of drying–wetting cycles increased. The transition occurred may be due to the presence of cracks that would create weak zones in soil, but significantly intensify the spatial variability of structure and, thus, led to different shear behaviour of specimens.
3. The effect of the first drying–wetting cycle on the shear strength is the greatest for the unsaturated clay. The shear strength increases slightly after the first drying–wetting cycle at lower net normal stress; at higher net normal stress, the effect of the first cycle on the shear strength is contrast.

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