

Influencing of drying-wetting cycles on mechanical behaviors of silty clay with different initial moisture content

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Abstract. To get a better understanding of the effect of drying-wetting cycles (DWC) on the mechanical behaviors of silty clay having different initial moisture content (IMC), the direct shear tests were performed on sliding band soil taken from a reservoir-induced landslide at the Three Gorges Reservoir area. The results indicated that, as the increasing number of DWC, the shear stress-displacement curves type changed from strain-hardening to strain-softening, and both the soil peak strengths and strength parameters reduced first and then nearly remain unchanged after a certain number of DWC. The effects of DWC on the cohesion were predominated that on the internal friction angle. The IMC of 17% is regarding as the critical moisture content, and the evolution laws of both peak shear strength and strength parameters presented a reversed 'U' type with the rising of the IMC. Based on it, a strength deterioration evolution model incorporating the influence of IMC and DWC was developed to describe the total degradation degree and degradation rate of strength parameters, and the degradation of strength parameters caused by DWC could be counterbalanced to some extent as the soil IMC close to critical moisture content. The microscopic mechanism for the soil strength caused by the IMC and DWC were discussed separately. The research results are of great significance for further understanding the water-weakening mechanicals of the silty clay subjected to the water absorption/desorption.

Keywords: direct shear test; drying-wetting cycles; initial moisture content; sliding zone soil

1. Introduction

Generally, geotechnical systems such as compacted embankments, accumulated landslides, landslide dams and shallow foundations are usually constituted by soils. The variations of soil shear strength are important for geotechnical systems stability (Fazeli *et al.* 2009, Rahnenma *et al.* 2003). A change in the climatic environment and/or reservoir operation imposes water absorption/desorption cycles to the subgrade soils, impacting the stability of the geotechnical systems. In the Three Gorges Reservoir area, the water level fluctuates between 145 and 175 m yearly, and the rainfall season and dry season usually corresponding to the drop and rise of reservoir water, respectively, which make the mobilized materials have different moisture content and suffer from the cyclically drying and wetting (Niu *et al.* 2023, Wang *et al.* 2022, Zhang *et al.* 2023, Zou *et al.* 2023).

Drying-wetting cycles can greatly influence soil properties such that a significant decrease in mechanical strength can be expected for bank slopes undergoing drying-wetting treatments. The water-weakening effect has widely recognized to be relevant to the reactivation of ancient landslides and the failure of accumulated landslide, where the displaced materials within the riparian zone

undergo periodic water fluctuation (Gupta *et al.* 2016, Lacerda 2007, Miao *et al.* 2022). In terms of the long-term instability of bank slopes induced by cyclic drying-wetting, the strength degradation of soil is of major concern (Castellanza *et al.* 2008). Over the past several decades, a large number of experimental studies have been carried out to investigate the influence of DWC on the hydromechanical behavior of soil (Gens *et al.* 2006). For example, based on a series of laboratory tests on the sliding zone soil, an empirical strain-dependent model was used to describe the strength reduction behavior of the slip zone soil, and this model was implemented in the finite element software for the purpose of simulating how the failure zone propagates within the landslide during reservoir impoundment (Chen *et al.* 2016b). The shear mechanical behavior of slip zone soil is studied by indoor repeated direct shear test, and shear constitutive model is established to evaluate the stability evolution of Outang landslide (Yan *et al.* 2022). Additionally, some attempts have been made to investigate the impact of drying/wetting on the mechanical behaviors of soils and show the shear strength characteristics of soils under drying/wetting treatments to be different (Guan *et al.* 2010). In general, the shear strength on the drying path is higher than that on the wetting path at a given suction due to hydraulic hysteresis (Gu *et al.* 2021, Nishimura and Fredlund 2002, Tse and Ng 2008). The higher degree of saturation on the drying path results in a larger contact area of water with soil particles, contributing to the increase in shear strength of soil when subjected to matric suction, as compared to that on the

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wetting path (Goh *et al.* 2014, Wheeler *et al.* 2003).

Apart from the influence of cyclically drying and wetting treatments, the factor of moisture content would also have capable of influencing the slope stability (Pei *et al.* 2020, Tohari *et al.* 2007). In terms of exploring the effects of initial moisture content (IMC) on the sliding zone soil shear mechanical responses, it has been analyzed by many scholars through different research methods. The shear behaviors of sliding zone soil of loess landslides vis ring shear tests has been conducted and the tests results indicated that under the condition of normal consolidation, the soil sample with the optimum moisture content has the highest shear strength (Zhu *et al.* 2022). In order to investigate the effect of moisture content on the sliding zone soil of the Lock's Head landslide, a landslide hyperbolic stress model was established using larger indoor direct shear experiment and the stress-deformation mechanism characteristics during different periods of rapid changes of moisture content was analyzed in detailed (Song *et al.* 2012). The fast shear test without drainage and consolidation was used to investigate the soil shear strength and failure process considering different moisture content (Chen *et al.* 2016a).

A detailed review of previous studies has revealed that most of the existing research results focus on the analysis of single influencing factor (Zhang *et al.* 2013), while the analysis of the coupling effect of multiple factors is relatively rarely. In other words, there is very little research taking the both factors of DWC and IMC into consideration together. As a matter of fact, the IMC for the soil at the different part of landslide, such as at the toe and rear part, is varied, which means that the mechanical properties of soil having different IMC will present different changes laws once the soil undergoing DWC.

In this study, to better analyze the mechanical behaviors of silty clay, a series of direct shear tests were conducted on sliding zone soil that obtained from a reservoir-induced landslide at the Three Gorges Reservoir area considering the factors of IMC and DWC. The mechanical responses including deformation, peak strength and strength parameters (cohesion and internal friction angle) were analyzed in detained. Based on it, the data were then compared to find the trend of the change in the total degradation degree and degradation rate of strength parameters, and to establish strength deterioration evolution model incorporating the influence of IMC and DWC. Finally, the microscopic mechanism for the soil strength caused by the IMC and DWC are discussed. These analyses are of great significance for understanding the mechanical decay mechanism of the silty clay with different IMC subjected to drying and wetting treatments, and also can provide some theoretical basis for the study of slope stability in a reservoir area.

2. Materials and methods

2.1 Testing materials and specimen preparation

The testing material used in this research, silty clay, was

sliding band soil and obtained from a trench that is located at the rear part of the reservoir-induced reactivated ancient landslide at the Three Gorges Reservoir area and the basic physical properties indexes are shown in Table 1. It can be seen that the particle size of the soil sample is mainly between 0.005 mm and 0.075 mm, among which the average content for sand, silt and clay is 21.43%, 64.52% and 14.05%, respectively. and plastic index is 11.08, which is between 10 and 17. According to the Unified Soil Classification System, ASTM D 2487-10 (ASTM, 2010), it is judged to a CL soil.

Following the recommended soil test method proposed by Test Methods of Soils for Highway Engineering, the silty clay (Fig. 1(a)), which was dried, crush and passed through a 2 mm sieve to remove coarse sand and gravel particles, was put into an electronic scale, then weighing required water and spraying it into the silty clay using spray bottle until the target/IMC achieved. After that, wrapped with cling film and left for 24 h to ensure that the moisture content of the silty clay remained consistent. It should be noted that the mass of water to be added in the silty clay of the target water content was calculated according to following formula (1)

$$m_w = 0.01(w - w_h) \frac{m}{1 + 0.01w_h} \quad (1)$$

Where m is the quality of the soil (g); w_h is soil moisture content (%); and w is the moisture content required for sample preparation (%).

Soil specimens with a diameter of 61.8 mm and a height of 20 mm were prepared with a cutting ring. The specimens were formed as follows: firstly, a pad with a thickness of 10 mm was placed at the bottom of the cutting ring and covered with a layer of cling film. Weighting the required silty clay that was filled into the cutting ring and compacted in layers. It should be noted that when the first layer of soil sample is compacted to 6-7mm, its surface was shaved, and then the same operations for the rest two layers of soil sample were repeated until the specified height was reached. Finally, the pad under the cutting ring was removed, and the soil specimens wrapped with cling file were left for 24 h. The partial soil specimens are shown in Fig. 1(b).

2.2 Test scheme and apparatus

Through the analysis of relevant literatures, it is understood that the influencing factors of shear behaviors of soil are mainly related to moisture content, dry density, matrix suction and temperature. This study focuses on the verifying the influence of DWC on the shear deformation and strength of silty clay with different IMC. Considering that the natural water content and optimal water content of silty clay in Table 1 is approximately 15% and 17%, respectively. Meanwhile, combined the recommendations from Test Methods of Soils for Highway Engineering and several literatures (Goh *et al.* 2014, Hu *et al.* 2018, Liu *et al.* 2015), the initial moisture contents (IMCs) in this study were set at 13, 15, 17, 19, and 21%. For drying/wetting, the

Table 1 Basic physical properties of silty clay

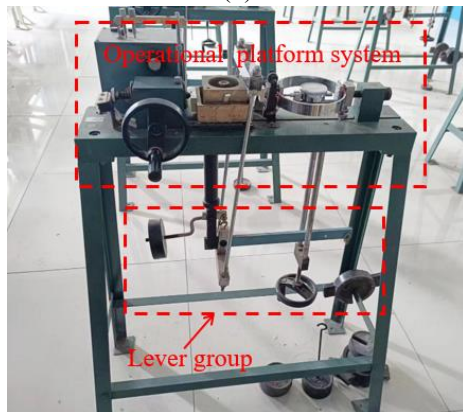
Type	Maximum density ($\rho_{d\ max}$)/g \cdot cm $^{-3}$	Liquid limit (w_L)/%	Plastic limit (w_P)/%	Plastic limit index (I_P)/%	Natural water content/%	Optimal water content/%	Grain composition (mm) and its content (%)		
							Clay (<0.005 mm)	Silt (0.005~0.075 mm)	The sand (>0.075 mm)
Silty clay	1.74	32.78	21.7	11.08	15.12	17.01	14.28	63.65	22.07



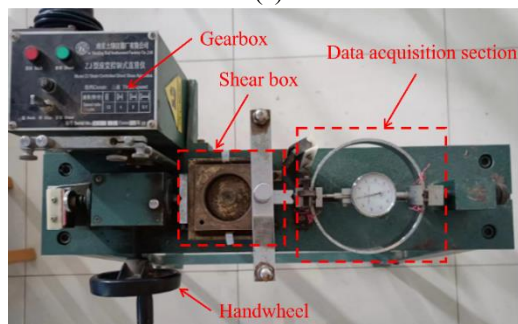
(a)



(b)



(c)



(d)

Fig. 1 The tests specimens and apparatus. (a) Crushed silty clay, (b) specimens, (c) ZJ-Direct shear test apparatus and (d) The system operation platform

remold specimens were firstly placed in a vacuum pot for 2 h and then immersed in distilled water for at least 24 h for saturation. once the specimens were saturated, they were air-dried in the laboratory at a temperature of 24~26°C. All air-dried specimens were carefully weighed per 24 h and the corresponding water content could be calculated. When the water content was close to the desired value, the weight of the specimen was measured at an hourly frequency. After the specimens achieved the specified water content, they were placed in the vacuum pot for saturation again. This process was repeated until the desired numbers of drying/wetting cycles was completed. Previous studies have indicated that soil structure reaches an equilibrium state after about three to five DWC (Liu *et al.* 2015, Nowamooz and Masrouri 2010), thus, the number of DWC were set to 0,1,2,3,4,5,10,15 and 20. Four objective normal loads (100 kPa, 200 kPa, 300 kPa and 400 kPa) were set to compress the specimens, and the horizontal shear load was applied by displacement-controlled mode (0.8mm/min in this study).

The shear tests were conducted on the ZJ-Direct Shear Test Apparatus that was manufactured by Nanjing soil instrument Factory Co., Ltd. The test apparatus mainly consisted of lever group and system operation platform (Fig. 1(c)). At the system operation platform, the sample preparation and shear test were carried out in the direct shear box. The stress during shearing is recorded by the data acquisition section, and the shear rate is controlled by the gearbox with handwheel (Fig. 1(d)). The shear strength under different normal pressures can be measured by adding or subtracting weights. The maximum vertical pressure of the instrument used is 400 kPa. The covering area of the tested sample is nearly 30 cm 2 and the height 2 cm. The strain-controlled direct shear instrument can measure the horizontal shear force when the soil is broken.

3. Test results

3.1 Shear deformation and strength characteristics

As space limited and the change laws of shear stress-deformation curves for the samples with different IMC submitted to multiple DWC is nearly the same, the shear test data for the samples have an IMC of 17% was selected and analyzed in detailed. Fig. 2 illustrated the shear stress-deformation curves of soil sample with 17% moisture content under different number of DWC. As shown in the picture, when the specimens submitted to no DWC, the shear stress-deformation curves presented strain-hardening properties, which is be characterized by the shear stress

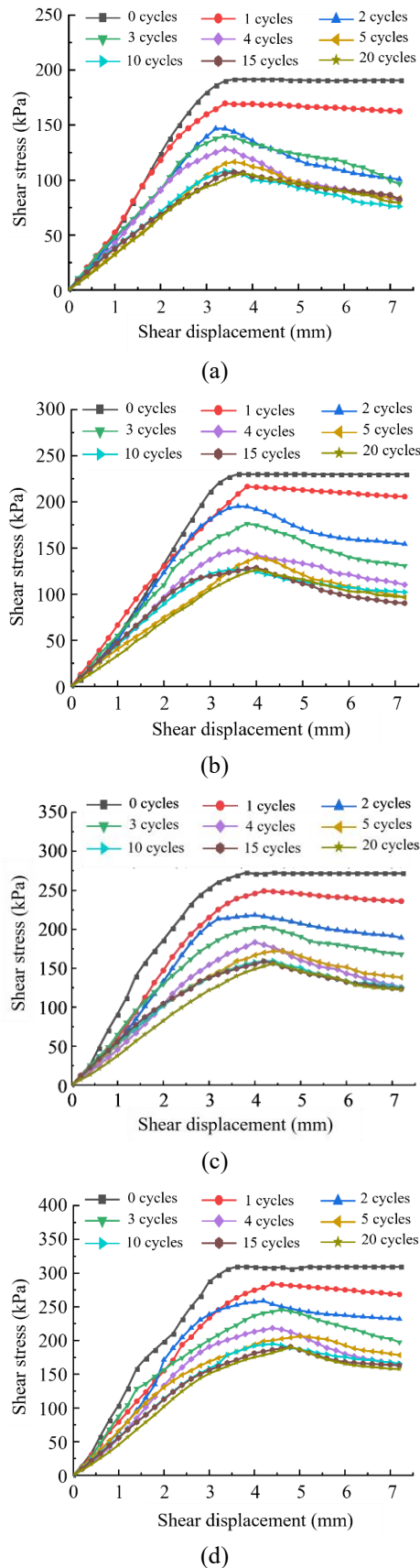


Fig. 2 the shear stress-deformation curves of soil sample with 17% moisture content under different number of DWC. (a) $\sigma_n=100$ kPa, (b) $\sigma_n=200$ kPa, (c) $\sigma_n=300$ kPa and (d) $\sigma_n=400$ kPa

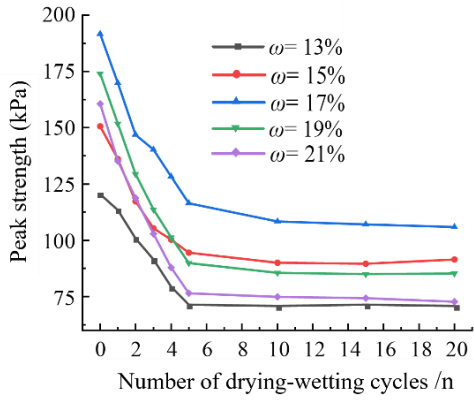
increased rapidly first and then keep constant nearly as the rising of shear displacement. Once the specimens subjected to one more number of DWC, the shear stress-deformation curves trended to be strain-softening phenomenon, which is featured with the shear stress increased first and then dropped to some extent as the rising of shear displacement. It means that the with the increasing number of DWC, the relationships between shear stress and shear displacement have a tendency of transiting from strain-hardening to strain-softening type, and the more number of DWC, the more significant signs of strain-softening.

Many literatures (Chao *et al.* 2023, Cheng *et al.* 2021, Lu *et al.* 2020, Liu *et al.* 2024, Cheng *et al.* 2024) already indicated that the DWC has capacity of deteriorating the shear strength, which was also proved in this study. As presented in Fig. 2, the peak strength of silty clay has negative correlation with the number of DWC. It also should be noted that the peak shear strength would not drop continuously with the increasing of the number of DWC. As shown in Fig. 2, as the number of DWC greater than 5, the shear stress-deformation curves are nearly overlapped, meaning that the peak strength is nearly constant. For example, in Fig. 2(a), the peak strength for the silty clay undergoing 10, 15 and 20 DWC, the peak strength is 108.41 kPa, 107.02 kPa and 105.93 kPa, respectively. The same phenomenon could also be found in Figs. 2(b)-2(d). Additionally, the relation curves between DWC and peak strength of specimens with different IMC (Fig. 3) also manifested that the DWC could impose the effect on the peak strength, which is characterized by that the peak strength reduced fast when the number of DWC is below 5, and then keep constant nearly.

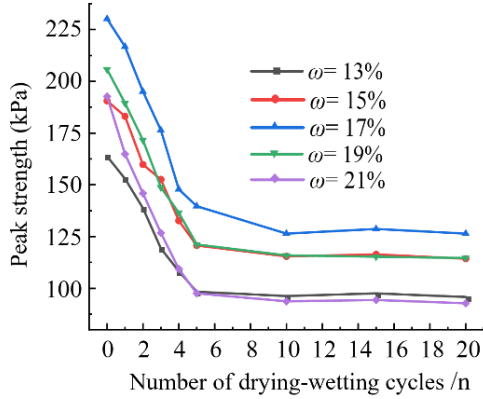
As see in Fig. 3, the peak strength usually increased first and then reduced with the rising of IMC, and the maximum peak strength occurred once the silty clay has an IMC of 17%. The possible explanation for it might be that the maximum dry density achieved when the moisture content of silty clay is 17%. Under this condition, silty clay structure is relatively compacted and most of the micro-pore and/or micro-fissure within the soil the is not filled with air but bonded water that has capable of binding the particles for the purpose of enhancing the strength of silty clay. The relationship between deterioration degree of peak strength after undergo 20 DWCs and IMC was shown in Fig. 4. The deterioration degree of peak strength usually decreased first and then increased with the rising of the IMC, and the minimum deterioration degree of peak strength occurred when the IMC is 17%, which manifest that the silty clay having optimal moisture content could restrict the deterioration effect imposing on strength caused by DWC to the utmost extent. Furthermore, the higher normal stress, the slighter deterioration of peak strength.

3.2 Shear strength parameters

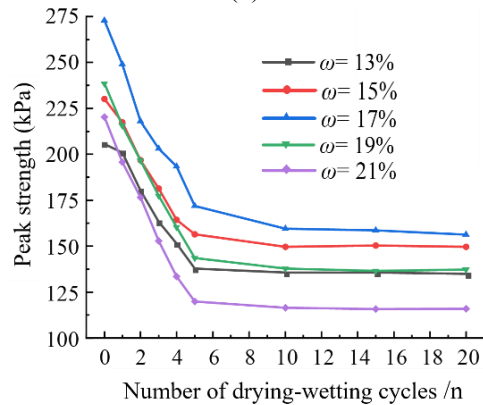
The relationships between the peak strength and normal stress for silty clay with different IMC after number of DWC were fitted using the Mohr–Coulomb failure criteria, and the shear strength parameters were obtained and presented in Fig. 5. As illustrated in the picture, generally,



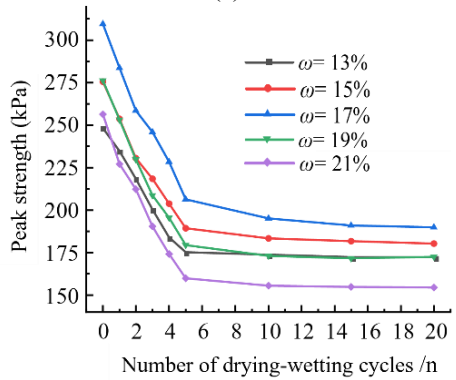
(a)



(b)



(c)



(d)

Fig. 3 The relation curves between DWC and peak strength of specimens with different IMC. (a) $\sigma_n=100$ kPa, (b) $\sigma_n=200$ kPa, (c) $\sigma_n=300$ kPa and (d) $\sigma_n=400$ kPa

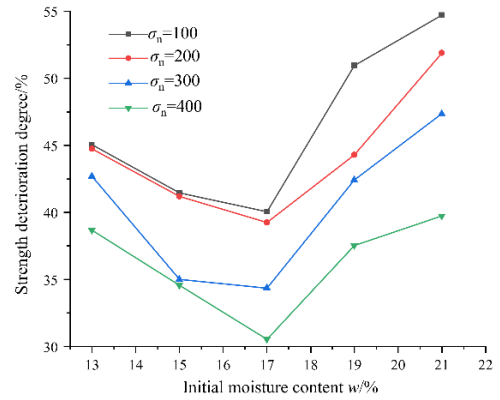
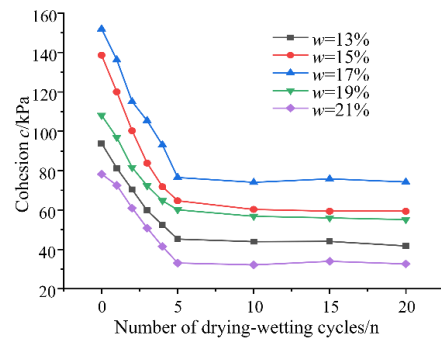
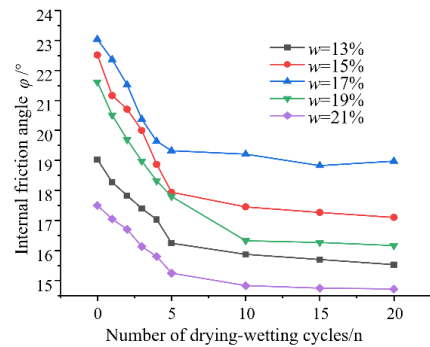


Fig. 4 The relationship between deterioration degree of peak strength after undergo 20 DWC and IMC



(a)



(b)

Fig. 5 The relationships between the strength parameters and DWC. (a) Cohesion and (b) Internal friction angle

the change laws of cohesion and internal friction angle for the silty clay with different IMC influenced by DWC were nearly the same, which is characterized by that the shear strength parameters decreased first and then fluctuated slightly and irregularly near a certain value with the increase in the number of DWC. A closer inspection of the results reveals that the shear strength parameters of the silty clay decrease more quickly during the first several cycles: the drop in cohesion after five DWC corresponds to nearly 80% of the total reduction in 20-cycles treatment. For example, a drop amplitude of 49.01kPa in five cycles treatment that corresponding to 78% of the total reduction in 20-cycles treatment occurred at the silty clay with an IMC of 21% (Fig. 5(a)). This is also pronounced for the friction angle: the decline of internal friction angle is

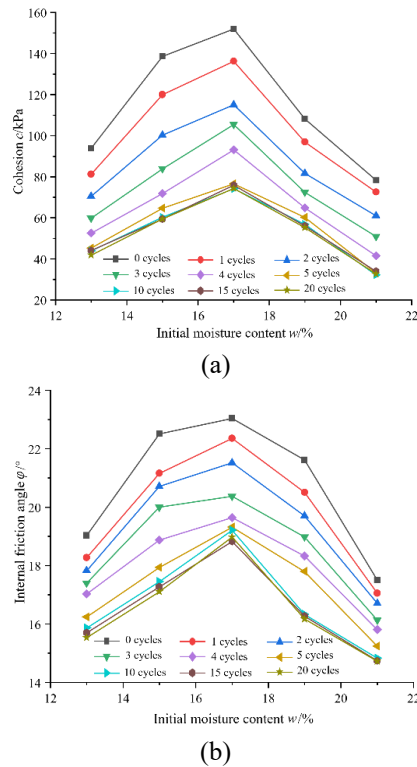


Fig. 6 The relationship curves between the IMC and shear strength parameters. (a) Cohesion and (b) Internal friction angle

slowing down after 5 DWC significant (Fig. 5(b)), which seems to corroborate the view that the shear strength will remain steadily unchanged after a certain number of DWC. A closer observation of Fig. 5 reveals that the DWC could impose more effect on the dropping of cohesion. As illustrated in Fig. 5(a), the minimum drop amplitude of cohesion after 20-cycles treatment is 51% (76 kPa) for the silty clay has an IMC of 17%. However, as shown in Fig. 5(b), the maximum drop amplitude of internal friction angle after 20-cycles treatment is 26.8% (4.8°) for the silty clay has an IMC of 21%

As manifested in Fig. 5, regardless of the number of DWC, both the maximum cohesion and the internal friction angle of the silty clay occurred when the IMC is 17%, which is proved in Fig. 6. As can be seen that the shape of relationship curves between the IMC and shear strength parameters is reversed 'U', which is characterized by that the shear strength parameters increased with the rising of IMC once the IMC is below 17%. For example, for the silty clay undergoing no DWC and having a rising IMC from 13% to 17%, the cohesion and internal friction angle increased from 93.84 kPa to 151.97 kPa and from 19.03° to 23.04°, respectively. However, once the IMC is above 17%, the shear strength parameters decreased with the increasing of IMC. For example, when the silty clay undergoes 5 DWC and having a rising IMC from 17% to 21%, the cohesion and internal friction angle decreased from 76.58 kPa to 33.06 kPa and from 19.32° to 15.24°, respectively. It should be noted that the correlation between IMC and shear strength parameters is contrary to the popular belief that the

mechanical properties of soil tend to decrease after water absorption. One possible explanation is that, as silty clay has an IMC of 17% (optimum moisture content), cohesive effect of matric suction (Fredlund and Rahardjo 1993, Thyagaraj and Salini 2015) and adhesive force (Risnes *et al.* 2005) of the clayey minerals will increase, which leads to a higher shear strength parameter.

4 Discussions

4.1 Strength deterioration evolution analysis

Based on the classical damage theory (Lemaitre 1984), considering the cohesion/internal friction angle before the wetting-drying process as the original state and the cohesion/internal friction angle after n wetting-drying cycles as the damage state, the degradation variable for the cohesion and internal friction angle of the silty clay ($D_{c(\varphi)}$) can be defined as below

$$D_{c(\varphi)} = \begin{cases} 1 - \frac{c_n}{c_0} \\ 1 - \frac{\varphi_n}{\varphi_0} \end{cases} \quad (2)$$

Where c_0 and c_n are the initial cohesion and cohesion after n DWC, respectively. φ_0 and φ_n are the initial internal friction angle and internal friction angle after n DWC, separately. According to Eq. (2), the degradation variables for cohesion and internal friction angle after different numbers of DWC were obtained and shown in Fig. 7.

Since soil material is composed of micro-units (mineral grains) with different strength, statistical methods are often used to describe the degradation state of micro-units caused by external disturbances, such as stress (Wang *et al.* 2007), cyclic freezing and thawing (Zhang *et al.* 2019), cyclic changes in relative humidity (Pineda *et al.* 2014) and cyclic drying-wetting (Mei *et al.* 2016). In this study, we proposed a mathematical model of hyperbolic function, which has capable of depicting the correlation between the degradation variables $D_{c(\varphi)}$ and number of DWC quantitatively and expressed as follows

$$D_{c(\varphi)} = \lambda_{c(\varphi)} - \frac{\lambda_{c(\varphi)}}{1 + \frac{n}{\beta_{c(\varphi)}}} \quad (3)$$

Where $\lambda_{c(\varphi)}$ is the total degradation for the cohesion and internal friction angle, which could be obtained by test directly; n means the number of DWC; $\beta_{c(\varphi)}$ was a parameter that expresses the degraded rate of cohesion and internal friction angle, and could be obtained by fitting the test data shown in Fig. 7. It should be noted that the smaller of $\beta_{c(\varphi)}$, the faster degraded rate of the shear strength parameters.

The fitting curves were shown in Fig. 7, and the corresponding fitting parameters were listed in Table 2. As

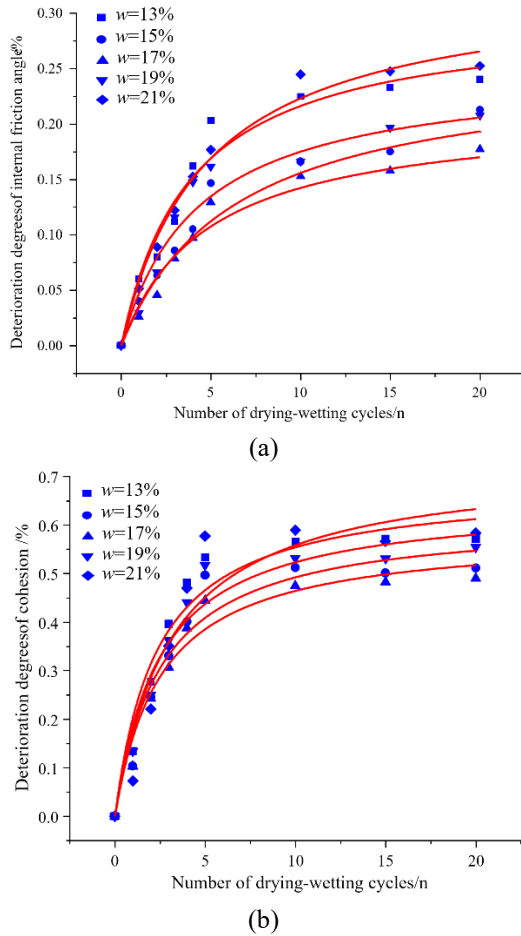


Fig. 7 (a) The degradation degree for cohesion after different numbers of DWC and (b) The degradation degree for internal friction angle after different numbers of DWC

can be seen that the almost all the correlation coefficients R^2 were larger than 0.94, indicating that the hyperbolic function could present well the relationship between the degradation variables and number of DWC. Fig. 8 shown the changes laws of between the degradation variables $D_{c(\varphi)}$ and IMC. As for cohesion, the total degradation (λ_c) and the degraded rate (β_c) were influenced by IMC significantly. Generally, with the increase of IMC, the total degradation of cohesion (λ_c) dropped first and then increased, and the minimum total degradation (51%) occurred as the silty clay has an IMC of 17% (Fig. 8(a)), it means that when the IMC below to a certain value, the degradation of cohesion caused by DWC could be counterbalanced by the increased IMC to some extent, above that, on the contrary, the increased IMC might result in higher degradation of shear strength parameters caused by DWC. Regarding to the internal friction angle, the value of λ_φ also decrease first and then increase as the increasing of IMC, and the maximum value of λ_φ occurred when the silty clay has an IMC of 17%. By comparing the total degradation of cohesion (λ_c) with the internal friction angle

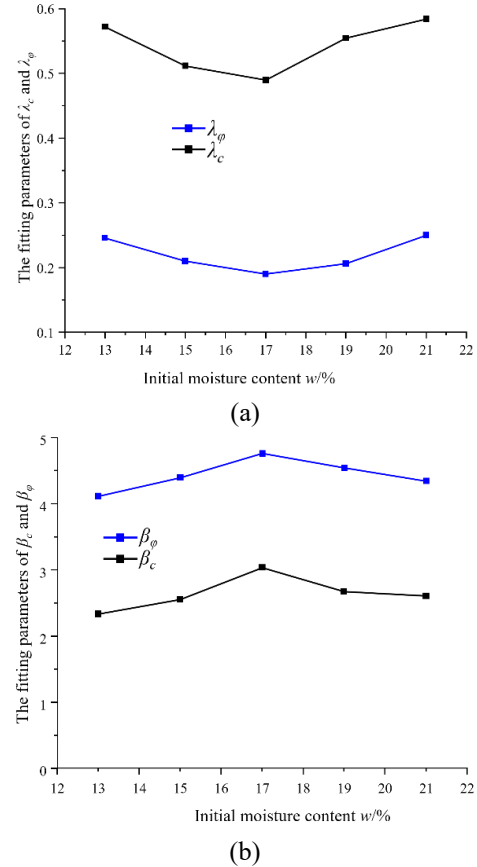


Fig. 8 (a) The relation covers between total degradation of cohesion (λ_c) and internal friction angle (λ_φ) and IMC and (b) The relation covers between degradation rate of cohesion (β_c) and internal friction angle (β_φ) and IMC

(λ_φ), the curve for the former is above the latter, meaning that the influences of DWC on cohesion were more dominated than that on the internal friction angle.

As for the degraded rate of the shear strength parameters (Fig. 8(b)), the maximum value of both β_c and β_φ occurred when the silty clay has an IMC of 17%. According to the definition of $\beta_{c(\varphi)}$, once the IMC within the silty clay is 17%, the smallest degraded rate of cohesion and internal friction angle achieved. Likewise, the curve of the β_c is below the β_φ , meaning that degraded rate for cohesion is faster than the internal friction angle. In other word, influences of DWC on the degraded rate of cohesion were more significant than that on the internal friction angle.

According to the Mohr–Coulomb failure criteria, strength deterioration evolution model for silty clay with different IMC (w) undergoing n DWC could be obtained and expressed.

$$\begin{cases} \tau_{w,n} = c_0(1 - D_c) + \sigma \tan[\varphi_0(1 - D_\varphi)] \\ D_c = \lambda_c - \lambda_c / (1 + n / \beta_c) \\ D_\varphi = \lambda_\varphi - \lambda_\varphi / (1 + n / \beta_\varphi) \end{cases} \quad (4)$$

Table 2 Fitting parameters of hyperbolic function for different values c and ϕ under different initial moisture content

Fitting parameters	$w=13\%$		$w=15\%$		$w=17\%$		$w=19\%$		$w=21\%$	
	c/kPa	ϕ°	c/kPa	ϕ°	c/kPa	ϕ°	c/kPa	ϕ°	c/kPa	ϕ°
λ	57.17%	24.6%	51.14%	21.01%	48.98%	19.01%	55.46%	20.62%	58.37%	25.01
β	2.3305	4.11353	2.55363	4.39493	3.03289	4.76017	2.67003	4.54431	2.60515	4.34386
R^2	0.94	0.97	0.95	0.97	0.96	0.96	0.95	0.97	0.97	0.96

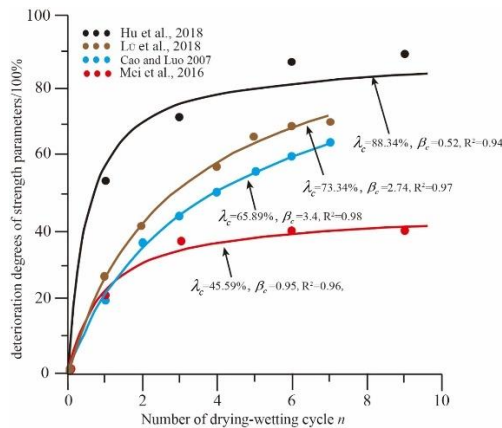


Fig. 9 The verification of proposed degradation evolution model using other tests data

For the purpose of verifying the correctness and applicability of the mathematical model proposed in this paper, some shear tests from other literatures were fitted using the proposed hyperbolic function (Cao and Luo 2007, Hu *et al.* 2018, LÜ *et al.* 2013, Mei *et al.* 2016), and the fitting results were shown in Fig. 9. As was seen, the correlation coefficients of this model are higher than 0.94, which suggests that the proposed model has capable of estimating the degradation evolution of shear strength properties of soil subjected to DWC.

4.2 Microscopic mechanism of shear strength evolution

Generally, the various of soil strength caused by the water-absorption has been widely recognized to be relevant to many slope failures, typically represented by the shallow deposited landslides, where the moisture content at the different section of the sliding body is varied. From a micro point of view, when there is a small amount of water in the soil, partial soil particles contact each other directly, the interaction between particles is mainly friction and the bonding is relatively weaker, causing that the soil has a low shear strength. As the moisture content increased (below the critical moisture content), on the one hand, the double electric layer structure within red clay has strong capable of water absorption for the purpose of forming a higher proportion of strong bonded water. Benefited the water film effects and the relatively larger electrostatic attraction between the particles, the shear strength increased. On the other hand, as the water was adsorbed by clay minerals, the gelatinous cement would be occurred to form a stable

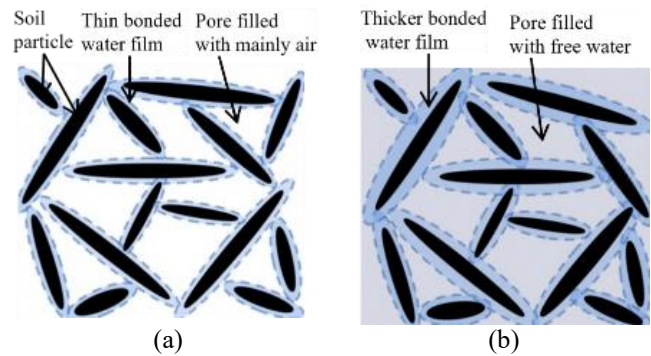


Fig. 10 Sketch of the change of thickness of bonded water film and water content in the pore as the increasing of initial moisture content; (a) Lower IMC and (b) Higher IMC.

agglomeration structure, which improved the shear strength of the soil. With the further increase of moisture content, that is, when the critical moisture content was reached, the above two effects would be enhanced to the maximum extent and shear strength would also achieve peak. After that, the bonded water film becomes thicker, and free water fills the pores (Zeng *et al.* 2022) (Fig. 10), weakening the water film effects and electrostatic attraction to some extent. Meanwhile, the amount and size of crumb will also increase, the structure of soil would be looser that is characterized by that the pore and fissures within the soil would be expanded and gradually be filled with water, causing the decreases of effective contact area between particles (Chen *et al.* 2021) (Fig. 11). As a result, soil shear strength has a tendency of reduction with the rising of moisture content. Thus, in this study, when the IMC lower than 17%, the soil shear strength increases with the rising of of IMC, above that, the rising IMC has capable of weakening the soil shear strength.

Many literatures indicated that the cyclic drying-wetting can greatly influence soil properties such that a significant decrease in mechanical strength can be expected for a soil undergoing drying and wetting treatment, which has also be proved by this study. Commonly, the shape of soil particles could be divided into angular and rounded, and the contact among particles can be classified as point and surface. After submitted to DWC, the proportions of angular grains decrease, but the rounded particles increase, both the number and degree of broken particles are rising, causing higher porosity (Mei *et al.* 2016). The higher porosity will decrease the cohesive effect of matric suction and adhesive force of the clayey minerals, and then weakening the soil

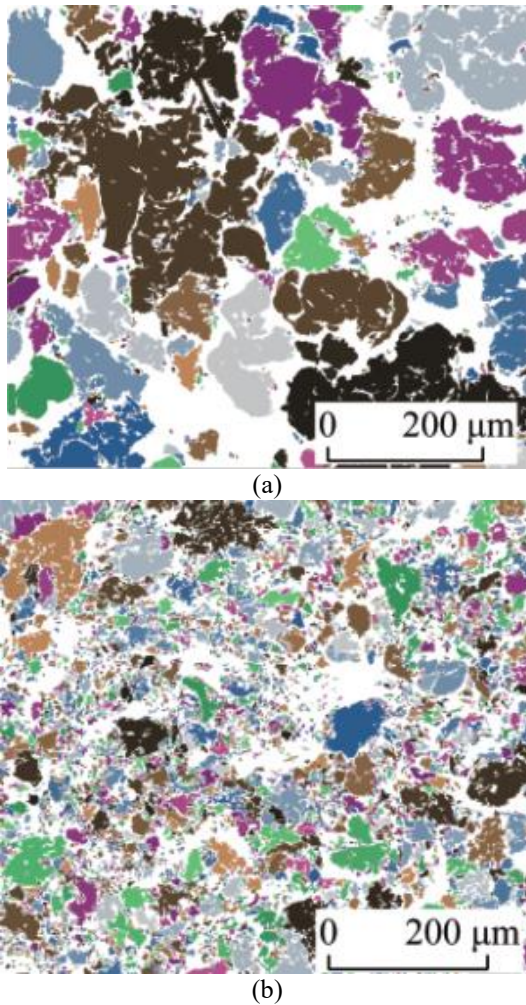


Fig. 11 The changes of soil structure and porosity as the increasing of initial moisture content; (a) Lower initial moisture content and (b) Higher initial moisture content. Note: Color region means soil particles and area marked with white means pore

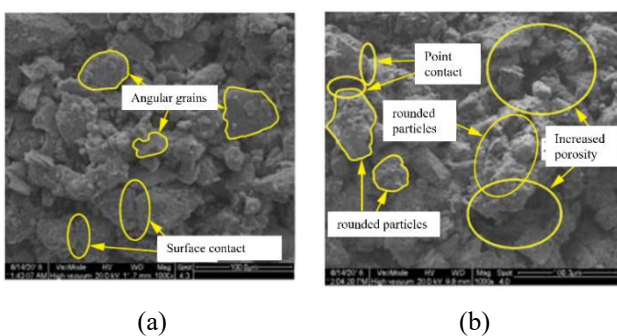


Fig. 12 The changes of soil shape and contact type between particles after several number of DWC; (a) The angular grains and surface contact is dominated before submitted to DWC and (b) The content of rounded particles and point contact is increased significant with higher porosity

strength. Additionally, the contact mode between particles was mainly in the form of surface before the DWC, while the point contact is dominated after the drying-wetting

treatment (Hu *et al.* 2018). The point contact has capable of damaging the friction and lock among the particles. The combined influence of the abovementioned—the changes in the shape and contact mode of soil particles— leads to the deterioration of soil shear strength (Fig. 12). It also should be noted that soil structure reaches an equilibrium state after a certain DWC, which means that the shape and contact mode of soil particles would not be changed continuously. Thus, in this study, the shear strength reduced at the first five cycles of drying and wetting, and after that, maintain nearly constant.

4.3 Limitations of the present study

It should be noted that there are a few factors that limited the generalization of the findings made in this study. For starters, different from the relatively larger dimension of samples used in direct shear test, the size of samples in this study is small (though it meets the sample size requirements recommended by the conventional experimental standards), which has few advantages to present the soil structure and/or the randomness. Many literatures demonstrated that the change laws of soil strength properties for small, middle and larger size samples are not consistent (Chen *et al.* 2023, Stoorvogel *et al.* 2019, Tavakoli *et al.* 2019). It means that the scale effect, especially for the direct shear tests adopted relative larger size of the samples, was recommended in the further study. Then, although we proposed a mathematical model to clarify the strength parameters evolution characteristics of soil undergoing DWC quantitatively, and demonstrate the correctness and applicability of the proposed model by fitting the shear tests results obtained from previous literatures, the validation of the proposed deterioration model is restricted to laboratory-scale shear tests. In other word, the engineering-scale application, especially for evaluating the slope stability, implemented the proposed degradation laws into numerical simulation software via developing customized code is lack. Therefore, in any future study, strength damage law of soil with different IMC submitted to DWC considering the size effects is worthy of study for the purpose of extending the proposed method to the application in actual engineering cases

5 Conclusions

The mechanical weakening of silty clay with different IMC induced by DWC is a well-known and extensively characterized phenomenon. However, the IMC of the soils at the different parts of the landslide is various, which has a significant influence on the soil strength. In this paper, the shear behaviors of sliding zone soil submitted to DWC considering the IMC were studied by performing direct shear tests. The main conclusions are as follows.

The increasing number of DWC has capable of transiting the shear stress-displacement curves from strain-hardening to strain-softening type, both the peak strengths and strength parameters decrease first and then the decline trend will slow-down obviously (nearly remain unchanged)

after a certain number of DWC. The effects of DWC on the cohesion are predominated that on the internal friction angle. The IMC of 17% is regarding as the critical moisture content. The total deterioration degree of peak strength usually reduced first and then increased as the rising of IMC. The maximum peak strength and the minimum total deterioration degree of peak strength occurred when the soil has a critical moisture content.

A strength deterioration evolution model incorporating the influence of IMC and DWC was developed to describe the strength parameters degradation degree and degradation rate. Generally, when the IMC below to a certain value, the degradation of strength parameters caused by DWC could be counterbalanced by the increased IMC to some extent, above that, on the contrary, the increased IMC might result in higher degradation of shear strength parameters caused by DWC. It should be noted that, although the proposed mathematical model has capable of depicting the strength deterioration quantitatively, the validation of the model is restricted to laboratory-scale shear tests using relatively small size samples.

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