

Study on Permeability and Triaxial Experiments of Clay under Wet-Dry Cycles and Compaction

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ABSTRACT: The permeability and mechanical properties of clay are significantly influenced by the seasonal wet-dry cycles and compaction. In this study, laboratory experiments were conducted to investigate the effects of the number of wet-dry cycles and compaction degree on clay behavior. The results indicated that the initial compaction degree had a significant influence on the permeability characteristics of soil specimens subjected to wet-dry cycles. Specifically, the permeability coefficients significantly decreased with increasing compaction degree. The measured permeability coefficients for low, medium, and high-compacted samples were 5.48×10^{-8} m/s, 8.33×10^{-9} m/s, and 7.29×10^{-10} m/s, respectively. After three wet-dry cycles, the permeability coefficients of the low and medium-compacted samples decreased to 1.16×10^{-8} m/s and 9.08×10^{-9} m/s, whereas that of the high-compacted sample increased to 6.76×10^{-9} m/s. A relatively strong linear relationship was observed between the permeability coefficient and the compaction degree on a semi-logarithmic plot. Both cohesion and internal friction angle increased with increasing compaction degree. With a growing number of wet-dry cycles, the failure mode of the specimens gradually transitioned from strain-hardening to strain-softening behavior. The modified Duncan-Chang model showed a relatively good fit for the stress-strain relationship of the sample. This research offers theoretical references and technical support for practical applications in clay-related engineering fields.

KEYWORDS: Clay, Wet-dry cycle, Compaction degree, Flexible wall permeability test, and Triaxial test.

1. INTRODUCTION

Clay is characterized by low permeability and high adsorption capacity, which make it effective in preventing the leakage and diffusion of pollutants such as landfill gas and leachate. Consequently, it is widely used in environmental geotechnical engineering, for instance, as lining materials for landfill closures and in radioactive waste repositories (Lin et al., 2025; Li et al., 2025). With the intensification of global climate change, seasonal water variability significantly affects the physical and mechanical properties of soils through repeated wetting–drying cycles (Bao et al., 2025; Chaudhary et al., 2024; Benson et al., 2020).

During wet–dry cycles, the fine pores in clay progressively expand and interconnect, forming a continuous pore network that increases permeability (Deng et al., 2026). Compaction, as a common soil improvement technique, enhances the density of clay and thereby reduces its permeability. However, excessive compaction may induce structural damage within the soil layer, potentially increasing its permeability. Omid et al. conducted both 10 cm flexible-wall permeability tests on compacted clay under wet-dry cycles and field double-ring infiltration tests. Their results showed that laboratory permeability tests significantly underestimate the proportional increase in the permeability coefficient of compacted clay subjected to wet-dry cycles (Omid et al., 1996). Drumm et al. performed permeability tests in different regions of fractured clay and demonstrated the presence of non-uniform structural damage in compacted clay under wet-dry cycles (Drumm et al., 1997). Rayhani et al. systematically discussed the influence of wet-dry cycles on permeability coefficients of various soil types, and through laboratory testing on large-scale fissured clay, determined the effect of sample size on the permeability coefficient of fracture soil (Rayhani et al., 2007; Rayhani et al., 2008). In terms of mechanical properties, compaction can enhance the shear strength and modulus of clay. However, a higher degree of compaction also

makes the soil more susceptible to volumetric shrinkage and crack development under wet-dry cycles. Ma et al. found that the cohesion of yellow clay exhibited a fluctuating overall decreasing trend with increasing numbers of wet – dry cycles, whereas the internal friction angle showed a slight overall increase (Ma et al., 2025). Liu conducted direct shear tests and observed crack propagation to elucidate the mechanisms of mechanical evolution in clay with different initial dry densities under wet-dry cycles (Liu, 2025). Shafqat investigated the effects of cyclic wetting–drying and initial compaction states on the mechanical behavior of various clays (Shafqat et al., 2025). The above literature indicated that relatively few experimental studies have simultaneously investigated the coupled effects of compaction and wet–dry cycles on both the mechanical behavior and permeability evolution of clay. To address this gap, the present study carries out relevant experimental research.

The main work of this paper includes the following aspects. First, the permeability coefficient of clay under different wet-dry cycle conditions was determined using flexible-wall permeability tests, and the variation in the permeability coefficient with the number of wet-dry cycles was analyzed. Second, the shear strength parameters, cohesion and internal friction angle, as well as stress-strain relationships and other mechanical indicators, were obtained through triaxial tests under various wet–dry cycle conditions. Finally, based on the experimental data and theoretical analysis, a permeability coefficient model incorporating the effect of wet – dry cycles and a modified stress – strain constitutive relationship was established for clay.

2. MATERIAL AND METHODS

2.1 Test Material

2.1.1 Fundamental Physical Characteristics

The density, water content, specific gravity, and consistency limits (liquid and plastic limits) of the soil sample were determined using the ring-knife method, oven-drying method, specific gravity bottle method, and combined liquid–plastic limit determinator, respectively. All tests were conducted in accordance with the Standard for Geotechnical Test Methods (GB/T 50123-2019), and the resulting basic physical parameters were summarized in Table 1.

Table 1 Basic physical properties

Specific Gravity	Moisture content	Density	Liquid limit	Plastic limit	Plasticity Index
2.74	20.5%	1.87g/cm ³	15	3	3

In accordance with the applicable classification method and the analytical results in Table 1, the soil sample is classified as silty clay.

2.1.2 Soil particle Distribution

Sieve analysis was performed to obtain the grain size distribution of soil particles in the range of 0.075mm to 2mm, after the soil had been dried and passed through a 2mm sieve. In addition, the grain size distribution of particles finer than 0.075mm was determined using the density meter (hydrometer) method. Based on the test results combining the sieving and hydrometer tests, the particle size distribution curve of the soil sample was presented in Figure 1.

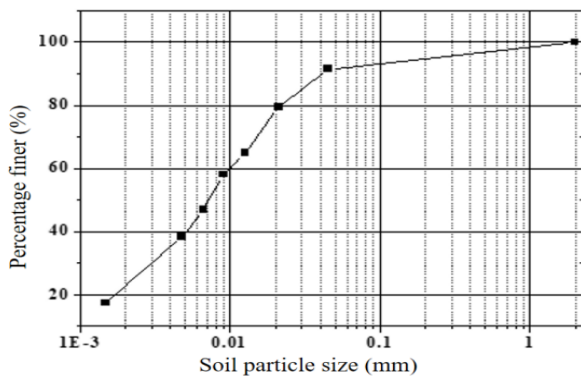


Figure 1 Grain size distribution curve of clay sample

The limit grain size of the soil sample was determined to be 0.01 mm, and the medium grain size was 0.003 mm. The curve also indicates that the soil sample comprises 7.2% sand-sized particles (>0.075 mm), 69.7% silt-sized particles (0.075–0.002 mm), and 23.1% clay-sized particles (<0.002 mm).

2.1.3 Mineralogical Characterization

X-ray diffraction (XRD) analysis was carried out to determine the mineral composition of the soil sample. The obtained diffraction diagram is shown in Figure 2.

As shown in Figure 2, the quartz content of the soil sample reached 69.2%, while the pyroxene content was 12.3%.

2.1.4 Compaction

A light compaction test was performed on the soil sample, and the obtained compaction curve is presented in Figure 3.

As shown in Figure 3, the optimal moisture content of the soil sample was determined to be 19%, and the maximum dry density was 1.74 g/cm³.

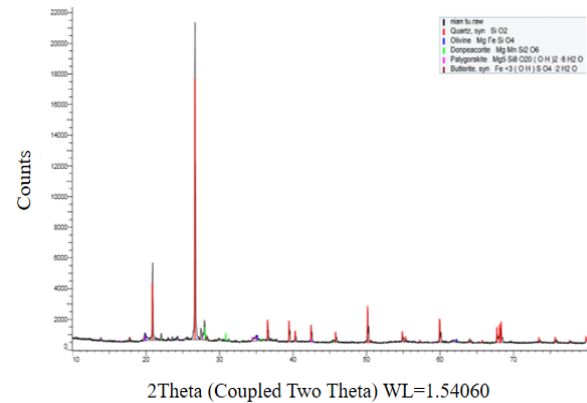


Figure 2 The X-ray diffraction result

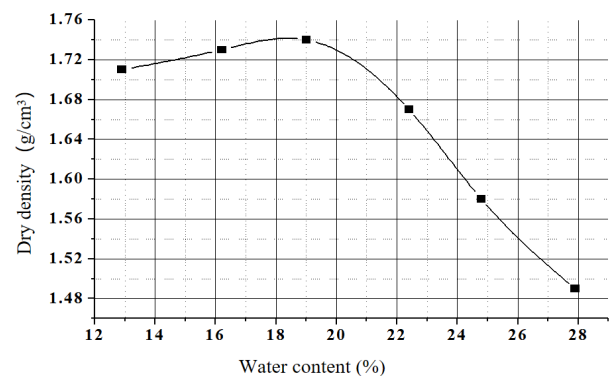


Figure 3 Compaction curve of clay sample

2.2 Test Methods

The specific testing methods and experimental plans for the permeability and triaxial tests conducted in this study are described below.

2.2.1 Permeability Test

For the permeability tests, five target dry densities of 1.57 g/cm³, 1.605 g/cm³, 1.64 g/cm³, 1.675 g/cm³, and 1.71 g/cm³ were selected, corresponding to initial compaction degrees of 90%, 92%, 94%, 96%, and 98%. denoted as Y90, Y92, Y94, Y96, and Y98. The number of wet-dry cycles was set to 0, 1, 2, and 3, designated as GS0, GS1, GS2, and GS3, respectively. For each wet–dry cycle, the soil specimens were first vacuum-saturated for 48 hours and then oven-dried at 50°C for 72 hours. This saturation–drying process was repeated until the predetermined number of cycles was reached.

The permeability test was conducted using the PN3230M flexible-wall penetration instrument (Yu et al., 2026), as illustrated in Figure 4. The test system consisted mainly of a control panel, a flexible-wall permeation cell, a pore-pressure measurement device, a dehydrator, and a specimen rubber membrane. During the test, the flexible membrane was pressed against the specimen under applied confining pressure, effectively preventing leakage along the sides caused by volume changes. The specimens were cylindrical, with a diameter and height of 5 cm. The soil was air-dried, crushed, and passed through a 2mm sieve, then adjusted to the optimal moisture content of 19%. According to the test scheme, the required soil mass for each specimen was calculated, and the sample was compacted in four layers within the compaction mold.

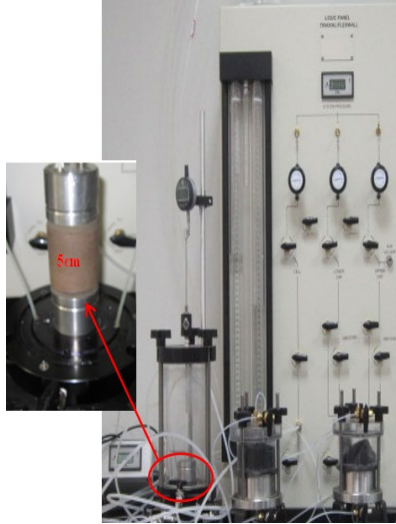


Figure 4 Flexible wall permeability testing equipment

2.2.2 Triaxial Test

Triaxial tests (Zhou et al., 2022) were carried out at dry densities of 1.57 g/cm³, 1.64 g/cm³, and 1.71 g/cm³, corresponding to compaction degrees of 90%, 94%, and 98% (Y90, Y94, and Y98), representing low, medium, and high compaction, respectively. The wet-dry cycles were 0, 1, 2, and 3 (GS0, GS1, GS2, and GS3), and the cell pressures were 30 kPa, 50 kPa, 100 kPa, and 150 kPa.



Figure 5 Strain-controlled triaxial apparatus

Laboratory triaxial tests were performed using a TSZ-6A strain-controlled triaxial apparatus, as shown in Figure 5. The soil was air-dried, crushed, and passed through a 2mm sieve, then mixed with water to achieve the optimal moisture content of 19%. Cylindrical specimens, 39.1 mm in diameter and 80 mm in height, were prepared by the static compaction method. Based on the target compaction degree specified in the test plan, the required soil mass for each specimen was calculated. The soil was then placed into the mold and compacted in three layers to form the specimens.

3. RESULTS AND ANALYSIS

3.1 Volume Shrinkage Results

After the wet-dry cycles, no obvious macroscopic cracks were observed in the specimens. This is primarily attributed to the small specimen size, which facilitated uniform dehydration and made it difficult to establish a hydraulic gradient conducive to cracking. After three wet-dry cycles, the volumetric shrinkage rates measured by the wax immersion method were 4.6%, 2.7%, and 1.7% for the low, medium, and high compacted specimens, respectively. The results indicated that all specimens underwent permanent volume

reduction after cyclic wetting and drying, and the magnitude of this reduction decreased with increasing compaction degree.

3.2 Permeability Test Results

The permeability coefficient of the specimens under different wet-dry cycle conditions were shown in Figure 6.

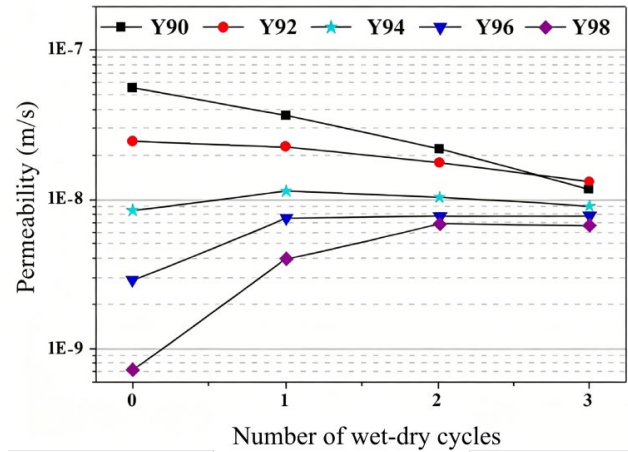


Figure 6 Permeability of compacted clay with different wet-dry cycles

As shown in Figure 6, the permeability coefficient of the specimens decreased progressively as dry density increased. Upon reaching a steady state of permeability, the coefficients for specimens with compaction degrees Y90 to Y98 were 5.48×10^{-8} m/s, 2.45×10^{-8} m/s, 8.33×10^{-9} m/s, 2.90×10^{-9} m/s, and 7.29×10^{-10} m/s, respectively. With increasing wet-dry cycles, the permeability coefficients of the low-compacted specimens (Y90 and Y92) gradually declined. For the moderately compacted specimen Y94, the coefficient initially increased and then decreased. Initial shrinkage–swelling deformation enhances hydraulic connectivity, while continued cycling generates migrating fine particles that gradually constrict and block flow channels (Chen et al, 2020). In contrast, the highly compacted specimens Y96 and Y98 exhibited a continuous upward trend in permeability coefficient throughout the cycling process. After three wet-dry cycles, the permeability coefficients for Y90 to Y98 were 1.16×10^{-8} m/s, 1.31×10^{-8} m/s, 9.08×10^{-9} m/s, 7.73×10^{-9} m/s, and 6.76×10^{-9} m/s, respectively. Notably, the permeability coefficients of the lower compacted specimens decreased significantly after wet-dry cycles, whereas those of the higher compacted specimens increased. These findings indicated that the impact of wet-dry cycles on the permeability coefficient of clay was closely related to the initial compaction degree of the specimen.

3.3 Permeability Coefficient Model

The relationship between the permeability coefficient of the specimen subjected to wet-dry cycles and its compaction degree was presented in a semi-logarithmic coordinate system in Figure 7. As shown in Figure 7, a strong linear correlation existed between the permeability coefficient and the compaction level on the semi-logarithmic plot. Based on linear regression analysis of the permeability coefficient against compaction degree in this semi-logarithmic space, the functional relationship between the two variables was established, as expressed in Equation 1.

$$\log K = a_1(n) + a_2(n)Y \quad n = 0,1,2,3 \quad (1)$$

In Equation (1), K denoted the permeability coefficient (m/s), Y represented compaction degree (%), n was the number of wet-dry

cycles, $a_1(n)$, $a_2(n)$ were the fitting parameters. The fitting coefficients were presented in Table 2.

Table 2 The results of the fitting parameters

n	0	1	2	3
$a_1(n)$	13.882	3.324	-1.491	-4.747
$a_2(n)$	-0.234	-0.119	-0.069	-0.035
R^2	0.989	0.964	0.944	0.906

The analysis of the fitting results indicated that when plotted on a semi-logarithmic scale, there was a distinct linear correlation between the permeability coefficient of the specimen and its degree of compaction. However, this linear relationship weakens slightly as the number of wet-dry cycles increases.

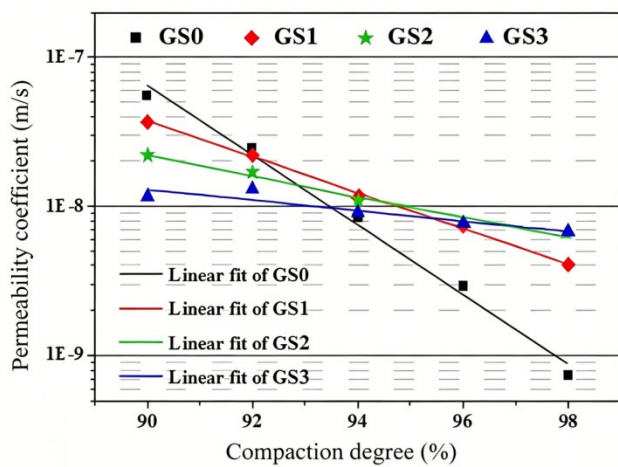


Figure 7 The relationship of clay permeability coefficient with compaction degree in semi-logarithmic coordinates

An exponential fitting was performed on parameters $a_1(n)$ and $a_2(n)$, and the relationship between these parameters, and the number of wet-dry cycles n was expressed in Equation 2.

$$\begin{cases} a_1(n) = 21.42e^{(-n/1.52)} - 7.58 \\ a_2(n) = -0.23e^{(-n/0.17)} + 0.01 \end{cases} \quad (2)$$

Both the linear fitting results for the permeability coefficient versus compaction degree (plotted on a semi-logarithmic scale) and the exponential relationships of the fitting parameters with the number of wet-dry cycles.

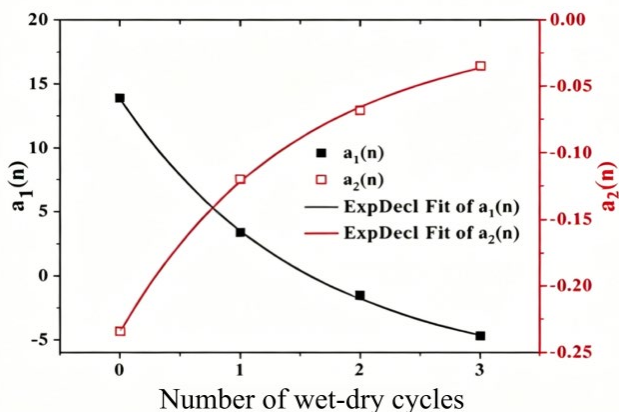


Figure 8 The exponential relation between different wet-dry cycles and the fitting parameters in Equation 2

The exponential relationship between $a_1(n)$, $a_2(n)$ and the number of wet-dry cycles n was clearly defined, with correlation coefficients of 0.997 and 0.998, respectively. Equations 1 and 2 collectively describe the variation in the permeability coefficient with both the degree of compaction and the number of wet-dry cycles.

3.4 Strength attenuation pattern

The variation pattern of peak strength and strength parameters of the specimens under wet-dry cycles was presented in Figure 9.

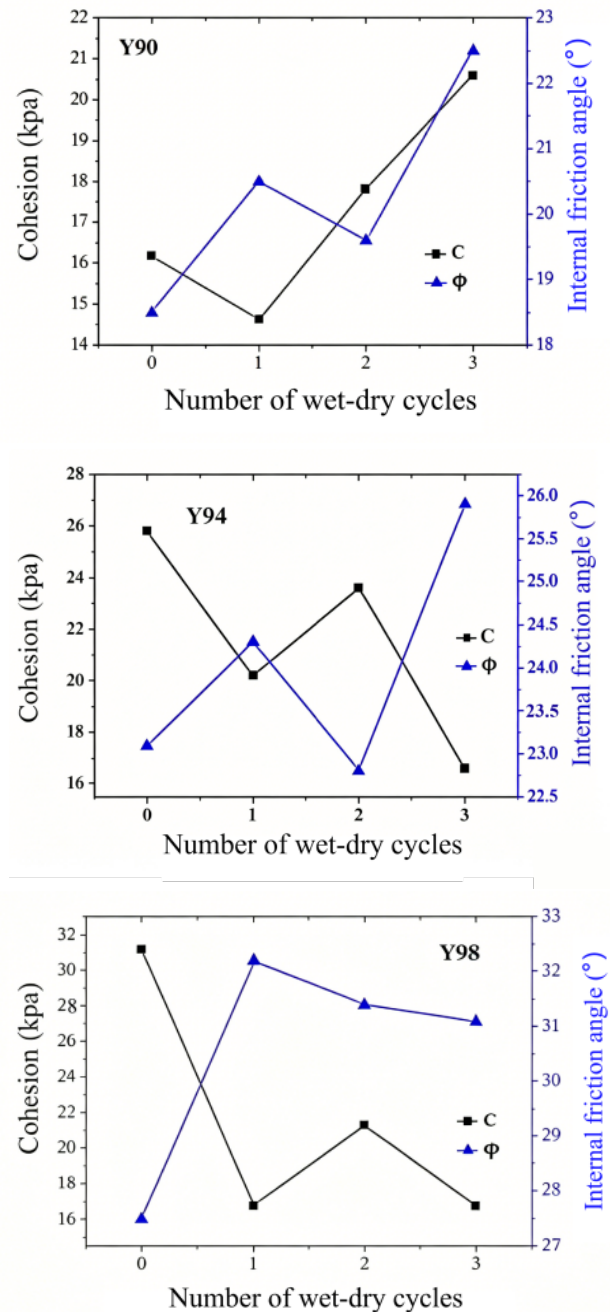


Figure 9 The strength parameters of compacted clay under different wet-dry cycles

The stress corresponding to 15% axial strain was defined as the peak strength. As the number of wet-dry cycles increased, the peak strength of low-compacted specimens showed a slight increasing trend, whereas that of the high-compacted specimens tended to decrease. The peak stress of the specimen gradually increased with

higher compaction degree and higher confining pressure. At a confining pressure of 30 kPa, the peak strength of all three compaction levels gradually decreased as the number of wet-dry cycles increased.

The cohesion and internal friction angle of the specimens both increased with higher compaction. Additionally, the internal friction angle tended to increase with the number of wet-dry cycles. For the low-compacted specimens, cohesion gradually increased with more cycles, whereas for the medium- and high-compacted specimens, cohesion showed a gradual decline as the number of cycles increased.

3.5 Stress-strain relationship

The stress-strain test results for the specimens subjected to wet-dry cycles were presented as scattered points in Figure 10.

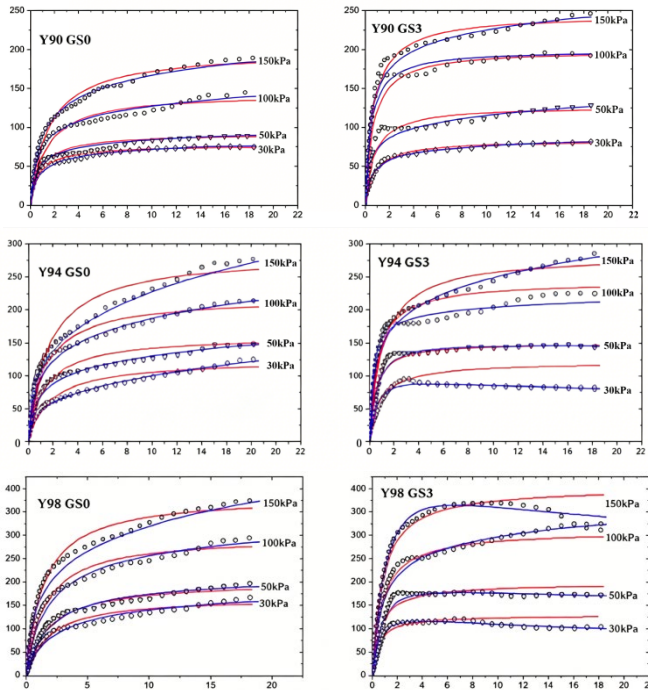


Figure 10 The stress-strain curve of compacted clay and the fitting curve of its constitutive model

As shown in Figure 10, under the influence of wet-dry cycles, the specimen stress increased with accumulated strain. The specimen demonstrated stiffness softening, as reflected by a gradual decrease in the stress rate with increasing strain.

The Duncan-Chang model (Yang et al., 2023; Huang et al., 2024). was an incremental elastic model derived from the hyperbolic stress-strain relationship, as presented in Equation 3.

$$(\sigma_1 - \sigma_3) = \frac{\varepsilon_1}{\frac{1}{E_0} + R_f \frac{\varepsilon_1}{(\sigma_1 - \sigma_3)_f}} \quad (3)$$

By transforming Equation 3, the linear decay relationship between clay stiffness and shear stress was derived, as shown in Equation 4.

$$E = E_0 \left(1 - R_f \frac{q}{q_f} \right) \quad (4)$$

In the above equation, R_f denoted the failure ratio; ε_1 was the axial strain; $(\sigma_1 - \sigma_3)$ was the deviatoric stress; $(\sigma_1 - \sigma_3)_f$ was the

deviatoric stress at specimen failure; $E = (\sigma_1 - \sigma_3)/\varepsilon_1$ was the modulus at stress of ε_1 .

The Duncan-Chang model was used to fit the stress-strain data of the specimens before and after wet-dry cycles, with the fitted curves shown as red lines in Figure 10. After three wet-dry cycles, the fitting performance deteriorated considerably. This is likely due to the stiffening behavior in the early strain stage and the substantial drop in stress at the latter stage of straining, both of which were induced by the wet-dry cycles.

The Duncan-Chang model was modified by adding a strain-softening factor $\left(\frac{\varepsilon_1}{\varepsilon_{1f}}\right)^n$ to Equation 4, and the updated stiffness model is shown in Equation 5.

$$\frac{E}{E_0} = 1 - R_f \frac{q}{q_f} \left(\frac{\varepsilon_1}{\varepsilon_{1f}} \right)^n \quad (5)$$

By converting Equation 5 into the form of Equation 3, the revised Duncan-Chang model was obtained, as shown in Equation 6.

$$(\sigma_1 - \sigma_3) = \frac{\varepsilon_1}{\frac{1}{E_0} + R_f \frac{1}{E_f} \left(\frac{\varepsilon_1}{\varepsilon_f} \right)^{n+1}} \quad (6)$$

where $E_f = q_f/\varepsilon_{1f}$ was the secant modulus corresponding to material failure.

The revised Duncan-Chang model was used to fit the stress-strain data of the specimens before and after wet-dry cycles, with the fitted curves shown as blue lines in Figure 10. The fitting results indicated that the modified Duncan-Chang model, which accounted for the effects of wet-dry cycles, provided a significantly better fit than the unmodified version.

4. CONCLUSIONS

This study conducted experiments on the permeability of clay under the influence of wet-dry cycles and compaction degree, and carried out in situ triaxial tests. The main conclusions of this manuscript were obtained as follows.

- (1) The permeability coefficients of specimens with low and medium compaction degree after three wet-dry cycles decreased from 5.48×10^{-8} m/s and 8.33×10^{-9} m/s to 1.16×10^{-8} m/s and 9.08×10^{-9} m/s, respectively. In contrast, the permeability coefficient of the high compaction specimen increased from 7.29×10^{-10} m/s to 6.76×10^{-9} m/s over the same number of cycles.
- (2) A relatively high linear correlation was observed between the permeability coefficient and the compaction degree when plotted on a semi-logarithmic scale.
- (3) Both cohesion and internal friction angle increased with rising compaction degree. Furthermore, the failure mode of the specimens gradually transitioned from strain-hardening to strain-softening behavior under wet-dry cycles.
- (4) The amended Duncan-Chang model incorporating strain-softening behavior demonstrated significantly superior fitting performance for the triaxial test data compared with the unmodified version, which could better simulate the actual mechanical properties of soil.

5. ACKNOWLEDGMENTS

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