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Experimental Study on the Mechanical Behavior Evolution of Cohesive Soils under Wet-Dry Cycling

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Abstract: Wetting-drying cycles induce structural changes and fissure development in cohesive soils, triggering geological disasters such as landslides. This study employs direct shear tests and fissure observations to elucidate the mechanical evolution patterns of cohesive soils with different initial dry densities during wetting-drying cycles. The key findings are as follows: 1) The shear strength decreases with an increasing number of wetting-drying cycles, with the most significant reduction occurring in the first cycle; 2) Theτ-S (shear stress-normal stress) curve exhibits a peak starting from the second wetting-drying cycle, and the peak value intensifies with subsequent cycles; 3) The surface fissure ratio is positively correlated with both the number of wetting-drying cycles and the initial dry density; 4) After multiple wetting-drying cycles, the shear strength of shallow soil layers tends to converge, and the influence of initial dry density diminishes.

1. Introduction

The increasing frequency of extreme weather events has subjected engineering cohesive soil slopes to prolonged wet-dry cycling. Structural alterations and mechanical property deterioration within these soils have become significant triggers for geological hazards such as landslides and debris flows. Therefore, investigating the mechanical behavior evolution of cohesive soils under wet-dry cycling holds both theoretical and practical importance.

Previous studies have yielded valuable insights into the physico-mechanical properties of soils under wet-dry cycling conditions. In terms of shear strength, research has revealed that the strength of unsaturated soils decays nonlinearly with an increase in moisture content [1]. An increase in the number of wetting-drying cycles significantly reduces the cohesion value (c) and induces shallow-layer landslides or slumps [2]. The relevant prediction models have been validated through statistical regression [3]and experimental verification [4]. Regarding the mechanism of fracture development, research indicates that the number of wetting-drying cycles and vertical pressure jointly regulate the propagation of fractures [5-7]. An increase in the sand content ratio can inhibit the in-depth development of fractures [8]. In the study of unconfined compressive strength, experiments have confirmed that the degradation pattern exhibits significant material dependency [9-11].

However, there are still critical gaps in existing research: namely, the quantitative relationship between initial dry density and the evolution of soil strength has not yet been established, and a systematic analysis of the multi-scale coupling mechanism between fracture network development and strength degradation is lacking. Therefore, in this study, by setting variables such as different initial dry densities and varying numbers of wetting-drying cycles, we observed the development of soil fractures after wetting-drying cycles. Through direct shear tests and unconfined compressive strength tests, we explored the influence mechanism of wetting-drying cycles on the strength of soils with different initial dry densities. This research aims to provide guidance and analytical data for the study of soil slope stability.

2. Materials and methods

2.1. Test Soil Samples

The soil samples used in the experiment were taken from a typical clay slope. To avoid interference from surface impurities, the soil was sampled at a depth of 1.5m. A series of basic physical property tests were conducted on the soil samples in the laboratory, and the resulting parameters are shown in Table 1. The soil samples collected from the field were placed in an oven set at 105°C and dried for 24 hours. After drying, the soil samples were crushed and passed through a 1mm geotechnical sieve to obtain the soil for experimental use.

Table 1: Natural basic physical property parameters of clay for test

natural density/g/cm^3	relative density	natural moisture content/%	plastic limit/%	liquid limit/%	plasticity index /%
1.78	2.72	26.7	11.6	32.7	21.1

2.2. Experimental Scheme

2.2.1. Direct shear experimental scheme

The soil specimens for testing were prepared by adding water to achieve a 20% moisture content, resulting in remolded soil samples with varying dry densities. Subsequently, samples for direct shear tests were obtained using a cutting ring with an inner diameter of 61.8 mm and a height of 20 mm. The initial dry densities of the specimens were controlled at three levels: 1.50 g/cm^3, 1.55 g/cm^3, and 1.60 g/cm^3. For each dry density, sixteen cutting ring specimens were prepared and divided into four groups of four specimens each, undergoing N (0, 1, 2, 3) cycles of wetting and drying. After completing the wetting and drying cycles, quick shear tests were conducted using a ZJ-type strain-controlled direct shear apparatus under normal stresses of 50, 100, 200, and 300 kPa, respectively.

2.2.2. Wetting and Drying Cycle Test Plan

The wetting and drying cycle consists of two stages: dehumidification (drying) and humidification (wetting). For the dehumidification stage, the specimens are placed in a 50°C forced-air drying oven for 20 hours and then weighed every 2 hours until a constant weight is achieved. For the humidification stage, the amount of water to be added is calculated based on the mass of the soil sample after dehumidification. A specific quantity of water is injected to restore the initial moisture content to 20%, and the sample is then sealed and left to stand for 6 hours to allow for uniform water distribution.

2.3. Analytical methods for the study of fissure development patterns

During the wetting and drying cycles of the direct shear test specimens, after each completion of a wetting and drying cycle, photographs are taken under the same ambient lighting conditions to document the fissure development of the specimens[12].Subsequently, the captured photographs undergo specialized quantitative processing using the PCAS system. The specific processing methods are as follows:

Firstly, the raw images are preprocessed by cropping the soil region and performing binarization to extract the fissure network. Finally, the surface fissure ratio is determined by calculating the ratio of fissure pixels to the total number of pixels. The quantitative analysis of fissures in the specimens after wetting and drying cycles focuses on the surface fissure ratio.

3. Experimental results

3.1. Results of the direct shear test

Figure 1 illustrates theτ-S relationships for soil samples with varying initial dry densities after different wetting-drying cycles (WDCs). Undisturbed samples (N=0) exhibit strain-hardening behavior with smooth, peak-free curves. Post-WDCs, τ-S curves develop distinct inflection points, and a peak indicative of strain-softening emerges after the second cycle.

Shear strength values were determined as either the 4 mm shear displacement stress (strain-hardening) or the curve peak (strain-softening). Figure 2 shows vertical stress (p) vs. shear strength (τ) plots: under identical pressure, shear strength decreases with increasing WDCs, with the largest reduction (~18%) occurring after the first cycle. Subsequent cycles show diminishing strength loss.

As shown in Figure 3 (N=0), shear strength increases with initial dry density under initial conditions. However, this correlation weakens in low-pressure ranges (50-100 kPa) after multiple WDCs, with strengths converging across densities after three cycles. High-pressure ranges (200-300 kPa) retain significant density-dependent trends despite cycling.

Overall, WDCs induce progressive strength degradation and homogenize shallow soil behavior, particularly at lower pressures.

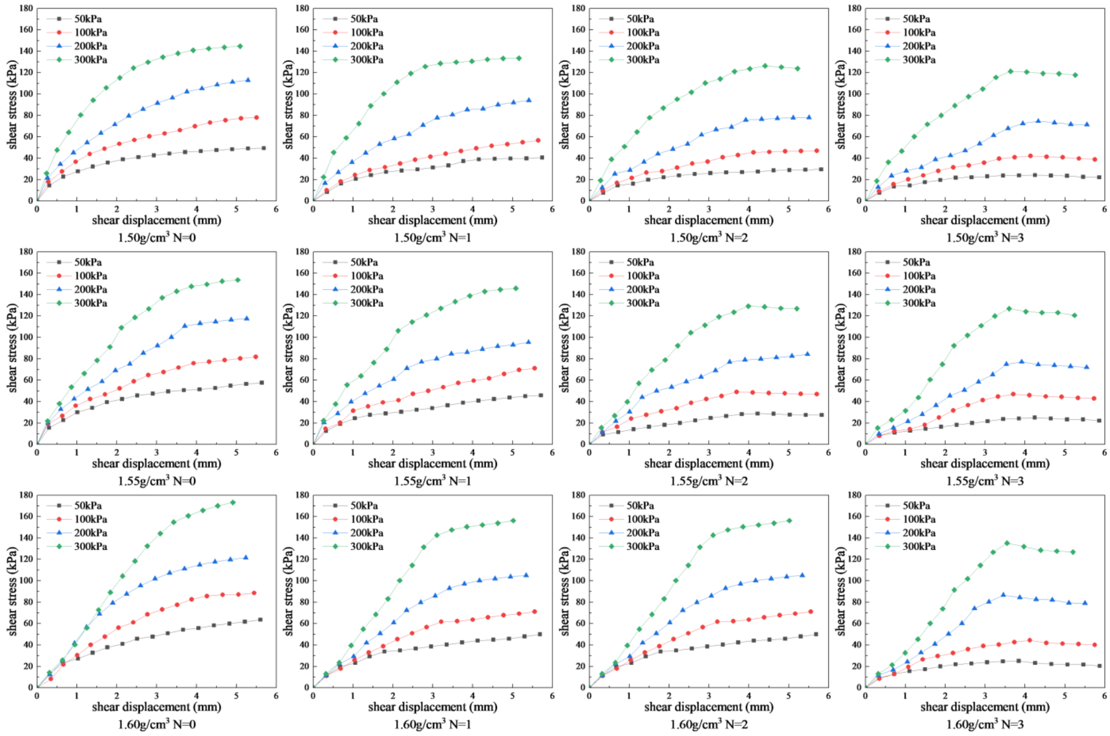

Figure 1: τ-S relationship of various initial dry density samples under different dry-wet cycle times

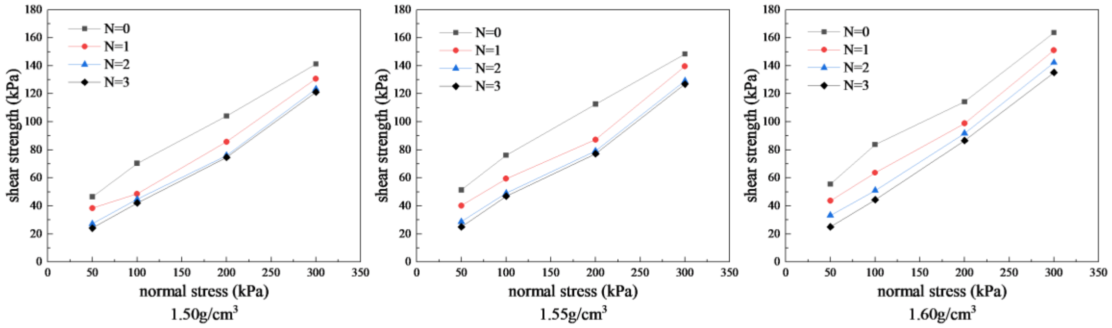

Figure 2: Shear strength changes of the three dry density samples under different dry-wet cycles

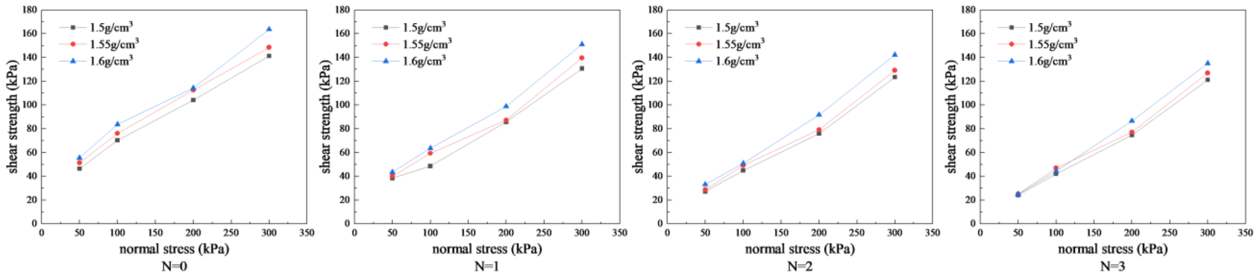

Figure 3: Changes in shear strength of samples with different dry densities after different dry-wet cycles

3.2. Observation results of fracture development

After undergoing wetting and drying cycles, the development of soil fissures in samples with different initial dry densities is illustrated in Figure 4. It can be observed from the figure that, as the number of wetting and drying cycles increases, the framework of soil fissure development gradually becomes clearer, with the length and width of the primary fissures progressively enlarging, and secondary fissures gradually emerging.

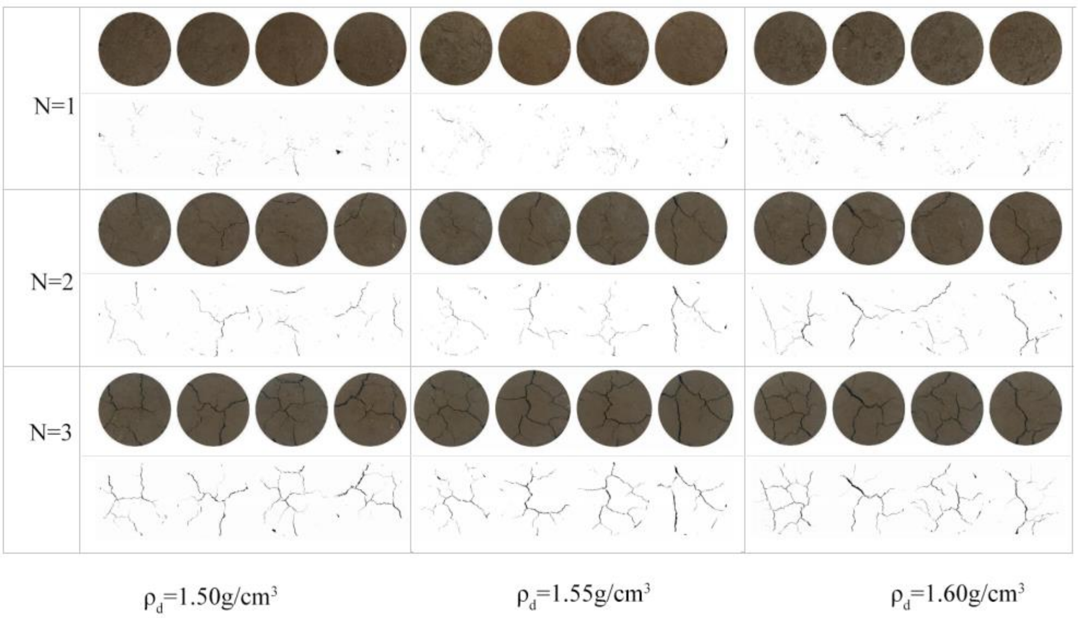

Figure 4: Fracture development and binary image of each group after dry-wet cycle

The surface fissure ratios (Rsc) of soil samples with different dry densities under varying numbers of wetting and drying cycles, obtained through binarization processing and analysis using the PCAS system, are presented in Table 2 and Figure 5. Analysis of the experimental results reveals that the surface fissure ratio of the specimens increases with the number of wetting and drying cycles (N). Moreover, the increase in the surface fissure ratio during the first two wetting and drying cycles is less pronounced compared to the effect of the third wetting and drying cycle. By comparing the values of the surface fissure ratio, it can be observed that, under the same number of wetting and drying cycles, the average surface fissure ratio of the soil samples shows a slight increasing trend with an increase in initial dry density.

Table 2: Surface crack rate of samples under various dry-wet cycles

Initial dry density/(g/cm^3)	Number N	Rsc(%)				Average Rsc (%)
		R50	R100	R200	R300	
	1	0.375	0.467	0.392	0.502	0.434
1.50	2	0.696	0.845	0.699	0.847	0.772
	3	1.403	1.437	1.571	1.851	1.566
	1	0.435	0.498	0.376	0.543	0.463
1.55	2	0.718	0.826	0.732	0.848	0.781
	3	1.327	1.683	1.888	1.825	1.681
	1	0.532	0.436	0.574	0.401	0.486
1.60	2	0.827	0.779	0.894	0.779	0.820
	3	2.079	1.791	1.901	1.379	1.788

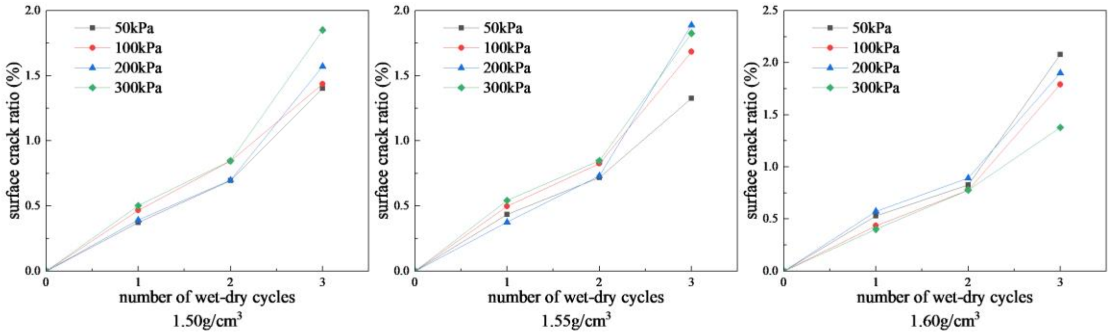

Figure 5: Relation of surface crack rate of samples with different dry densities with the number of dry-wet cycles

4. Discussion and analysis

The wetting and drying cycle process of cohesive soil involves dynamic water loss and absorption. During the desiccation phase, the thickness of the water film on soil particle surfaces gradually decreases, and particle spacing shortens due to the surface tension of the water film. This induces stress redistribution within the soil mass and generates localized tensile stresses. When the tensile stress exceeds the interparticle cohesion, initial microfissures form. Although macroscopic fissures are not yet visible at this stage (see Figure 4N=1), the internal soil structure has already been damaged, resulting in significant reductions in shear strength and unconfined compressive strength (see Figures 2 and Table 2). With increasing cycle numbers, existing microfissures progressively propagate and interconnect, eventually forming a macroscopic networked fissure structure (see Figure 4N=2 and N=3). The development of this networked fissure structure further weakens the shear strength, but the localized soil regions separated by fissures exhibit partial strength enhancement due to more uniform stress distribution and tighter particle connections caused by water film tension during desiccation. Influenced by these dual mechanisms, the rate of strength degradation in subsequent cycles becomes significantly slower compared to the first cycle (see Figures 2 and Table 2).

During soil desiccation, localized regions separated by microfissures experience densification due to surface tension of the water film, which tightens particle arrangements and forms compacted structures that remain unaltered during subsequent wetting phases. Consequently, the τ-S curves from direct shear tests on cycled soils exhibit peak characteristics (see Figure 1N=2 and N=3), demonstrating strain-softening behavior typical of overconsolidated soils.

The initial dry density of soil is inversely related to pore volume, with higher dry density corresponding to tighter particle packing. The wetting phase exacerbates particle rearrangement tendencies by reducing interparticle friction, while the liquid-gas interface tension formed during desiccation expands the compacted structural zones. This results in more pronounced tensile fractures and a slight upward trend in macroscopic surface fissure ratio with increasing initial dry density (see average surface fissure ratios in Figure 1). Although high-dry-density soils exhibit higher initial shear strength, their greater surface fissure ratios accelerate strength degradation. After multiple wetting and drying cycles, the shear strengths of soils with different initial dry densities converge (see Figure 3 for p=50 kPa and p=100 kPa). When higher vertical stresses are applied, fissure healing effects are enhanced, reducing the surface fissure ratio and mitigating the strength-weakening effect of fissures. Consequently, high-dry-density soils maintain their strength increment with dry density even after cycling (see Figure 3 for p=200 kPa and p=300 kPa).

5. Conclusions

By simulating the wetting and drying cycle process of unsaturated cohesive soil through laboratory experiments, and setting two variables—initial dry density and the number of wetting and drying cycles—direct shear tests, fissure development observations, and unconfined compressive strength tests were conducted on cohesive soil. The following conclusions were drawn:

(1) The shear strength of the soil decreases with an increase in the number of wetting and drying cycles. The first wetting and drying cycle has the most significant attenuating effect on the soil's shear strength. As the number of wetting and drying cycles increases, the rate of shear strength degradation decreases substantially.

(2) The surface fissure ratio of the soil increases with an increase in the number of wetting and drying cycles. Under the same number of wetting and drying cycles, there is a slight tendency for the surface fissure ratio of soil samples to increase with an increase in initial dry density.

(3) Wetting and drying cycles weaken the enhancing effect of initial dry density on the shear strength of shallow cohesive soil in slopes. Regardless of the initial dry density, the shear strength of shallow cohesive soil in slopes tends to converge after multiple wetting and drying cycles.

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