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Zhong Nie

School of Civil Engineering, Shandong Jianzhu University

Xinglong Luo

Shandong Provincial Geo-mineral Engineering Exploration Institute

Guangbiao Shao

School of Civil Engineering, Shandong Jianzhu University

Xiangzheng Li

plglxz@163.com

Penglai Pavilion Scenic Area Management Service Center

Chuanzhong Yao

Shandong Provincial Hydrogeology and Engineering Geology Co., Ltd

Zhaocheng Liu

Shandong Provincial Geo-mineral Engineering Exploration Institute

Guorui Yang

School of Civil Engineering, Shandong Jianzhu University

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Experimental Study on the Evolution of Mesoscopic Structure and Macroscopic Mechanical Properties of Typical Karst Fillings soil under Dry-Wet Cycles

NIE Zhong^{1,2}, LUO Xinglong³, SHAO Guangbiao^{1,2}, LI Xiangzheng^{4*}, YAO Chuanzhong⁵, LIU Zhaocheng³, YANG Guorui¹

- 1.School of Civil Engineering, Shandong Jianzhu University, Ji'nan 250101, China
- 2. Engineering Research Institute of Appraisal and Strengthening of Shandong Jianzhu University Co., Ltd, Ji'nan 250013, China
- 3. Shandong Provincial Geo-mineral Engineering Exploration Institute, Jinan, 250014, China
- 4. Penglai Pavilion Scenic Area Management Service Center, Penglai, 265600, China
- 5. Shandong Provincial Hydrogeology and Engineering Geology Co., Ltd., Jinan, 250014, China

Corresponding Author: LI Xiangzheng
Address: Penglai Pavilion Scenic Area Management Service Center, Penglai, 265600, China
Tel: +86-13583122085
Fax: 86-531-86367232
Email: plglxz@163.com

Abstract

The limestone formation in the Jinan area belongs to a typical karst development zone in northern China. Initially, basic physical tests were conducted on karst fillings from typical sites in the Jinan area. The data indicated that the fillings exhibit moderate expansion potential, with high montmorillonite content being the cause of their expansibility. Further tests were carried out on the expansive karst fillings, including free swelling ratio tests under dry-wet cycles, mercury intrusion porosimetry tests, and triaxial tests. The specimens were subjected to 1, 3, 7, and 11 dry-wet cycles. The findings are as follows: (1) Multiple dry-wet cycles significantly reduce the expansibility of karst fillings. (2) After 11 dry-wet cycles, the total pore volume increased by 83%, with the proportion of large pores rising from 6% to 49%, indicating a significant deterioration in the microstructure of the karst fillings. (3) With an increase in the number of dry-wet cycles, the shear strength decreased noticeably, and the elastic modulus declined exponentially, stabilizing after a reduction of approximately 38% following 3 cycles. The rate of shear strength decline was relatively uniform, with an eventual deterioration of about 40%. Quantitative relationships between elastic modulus, shear strength, and the number of dry-wet cycles were established based on experimental data. Stress paths and effective stress ratio curves revealed a strain-softening effect in the karst fillings after dry-wet cycles, gradually exhibiting ductile failure. As the number of cycles increased, repeated expansion and contraction weakened the cementation between particles, making them more prone to rearrangement and compaction. This led to a 1.3-fold increase in the maximum static pore water pressure during the tests. Based on the results of mercury intrusion porosimetry and triaxial tests, a progressive macro-micro damage evolution pattern was established, revealing the intrinsic correlation between microscopic damage evolution and macroscopic mechanical deterioration of karst fillings under dry-wet cycles. This study provides valuable references for engineering construction in karst areas.

Keywords: karst filling, dry-wet cycle, expansibility, pore characteristics, strength characteristics

1. Introduction

China hosts the world's most typical and complete karst landforms, with a terrestrial karst area of nearly 340×10^4 km². The underground karst landforms in northern China are predominantly composed of pores, fissures and karstified fissures, which locally combine with caverns to form a network structure. Shandong Province ranks among the regions with the most extensive distribution of temperate karst across northern China and the globe. Its exposed karst area is approximately 1.62×10^4 km², accounting for 10.34% of the total land area of Shandong Province.

At present, systematic investigations focusing on mechanical deterioration and microstructural damage evolution of karst fillings under alternating dry-wet conditions remain insufficient. Related research achievements on conventional expansive soils can provide important theoretical references for this study. In terms of shear strength evolution under cyclic drying and wetting, Rabbi

et al [1] clarified the variation rule of unsaturated expansive soil shear strength controlled by matric suction during repeated dry-wet cycles via laboratory mechanical tests. Ozer et al [2] further pointed out that initial water content is a critical factor dominating the shear mechanical response of expansive soils under hydrothermal cyclic fluctuations. Nowamooz et al [3] revealed the inherent correlation between soil internal fabric reconstruction and suction variation of compacted swelling soil after multiple dry-wet treatments, and verified that the loss of interparticle cohesion dominates the overall attenuation of shear strength. Puppala et al [4] confirmed that the continuous generation of surface and internal cracks triggered by cyclic moisture change accelerates the irreversible degradation of soil shear strength, while Fattah et al [5] supplemented the coupled influence of dry-wet and freeze-thaw cycles on the compression deformation properties of high-plastic expansive clay. Targeted at soil improvement against dry-wet damage, Sivapullaiah et al [6] proved that blended modification with fly ash and plant fiber can effectively restrain strength deterioration caused by periodic moisture alternation.

From the perspective of microscopic damage mechanism, existing studies mostly concentrate on crack development and pore structural variation induced by dry-wet cycling. Peron et al [7] explored the initiation and expansion law of desiccation cracks for medium expansive clay under diverse dry-wet boundary environments. Di Matteo et al [8] adopted mercury intrusion porosimetry (MIP) to quantitatively characterize pore structural damage of compacted expansive soil after cyclic dry-wet exposure and linked pore coarsening behavior to macro mechanical degradation. Ferber et al [9] used CT scanning technology to realize three-dimensional quantitative characterization of shrink-swell crack network evolution inside clay matrix under repeated drying and wetting. Nahlawi et al [10] analyzed aggregate expansion and microscopic pore transformation characteristics of expansive soils before and after water immersion based on SEM micrographs.

Regarding hydraulic performance evolution, Albrecht et al [11] experimentally concluded that continuous crack propagation stemming from dry-wet cycle is the core reason for the gradual increase of soil permeability coefficient. In the field of expansibility research, Al-Homoud et al. [12] found that repeated hydration and dehydration destroys the original particle stacking structure of clay, leading to progressive decay of free swelling potential. On the basis of suction-controlled dry-wet tests, Nowamooz et al [13] elaborated the hydro-mechanical coupling behavior of bentonite-silt mixed expansive soil and its compressibility change induced by cyclic wetting-drying. Al-Mukhtar et al. [14] compared the disparity in macro mechanical indexes and microscopic fabric between lime-modified and raw expansive clay, revealing the regulation mechanism of curing agent on restraining dry-wet deterioration of expansive soil.

Above abundant experimental and theoretical findings on expansive soils lay a solid research foundation for analyzing the macro-micro deterioration law of high-montmorillonite karst filling in Jinan under dry-wet cycles.

2. Soils and Basic Physical Tests

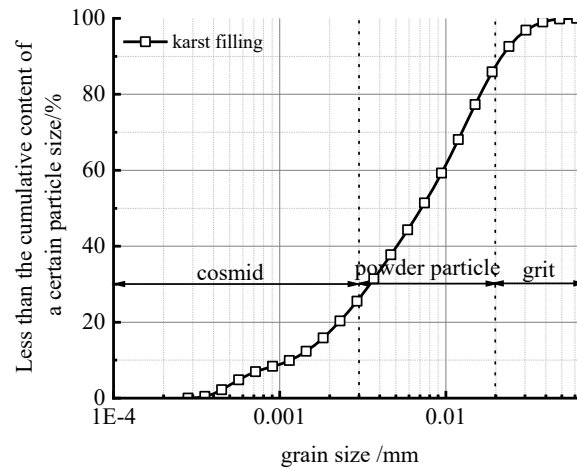
2.1. Test Soils

A typical karst terrain site in the Jinan area is illustrated in Fig. 1. The upper portion consists of alluvial-proluvial deposits, whereas the lower portion is characterized by intensely karstified bedrock, in which abundant fully filled karren, dissolution grooves, and caves were exposed during field investigation. The karst infilling is a brownish-red silty clay that densely packs the cavities, with occasional gravel clasts. Borehole data reveal that the site strata are predominantly composed of Holocene and Upper Pleistocene loess-like silty clay and cohesive soils of slope-proluvial origin, underlain by a weathered zone of Ordovician argillaceous limestone and limestone.



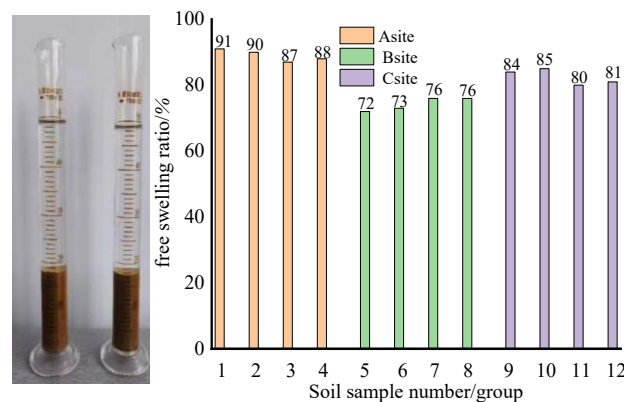
Fig. 1. Karst fillings Sampling site

Laboratory tests for water content, natural density, liquid and plastic limits, and particle size distribution were conducted on samples of the karst infilling in accordance with the Standard for geotechnical testing method (GB/T 50123-2019) [15]. The natural water content of the infilling is 22.7%, the natural density is 1.5 g/cm³, the liquid limit is 31.9%, the plastic limit is 19%, and the plasticity index is 12.9. The particle size distribution curve is shown in Fig. 2, with a clay fraction of approximately 30%, a silt fraction of approximately 57%, and a sand fraction of approximately 13%. Owing to the high silt content, the silt skeleton is prone to softening upon wetting. Meanwhile, the plasticity index exceeding 12 classifies the soil as medium- to high-plasticity, and the clay fraction exhibits pronounced swelling upon water absorption and shrinkage during drying. To avoid detrimental effects of the strong water sensitivity of the karst infilling on foundations, further tests for free swell ratio and mineral composition are required.

**Fig. 2.** Particle gradation of karst fillings

2.2. Free Swell Test

To ensure the representativeness of the test data, samples were collected from three typical karst sites in Jinan, and twelve sets of specimens were prepared from different sampling points for free swell tests. According to the test results, the average free swell ratio of the twelve karst infill specimens is 81.9%. In accordance with the identification method for expansive soils and the classification of swelling potential stipulated in the current Chinese national standard Technical Code for Buildings in Expansive Soil Regions (GB 50112-2013) [16], a free swell ratio between 65% and 90% ($65\% \leq \delta_{ef} < 90\%$) indicates medium swelling potential. Therefore, the typical karst infilling in the Jinan area can be identified as having medium swelling potential, and the detailed test results are presented in Fig. 3.

**Fig. 3.** Free expansion rate test and test results statistics

2.3. X-ray Diffraction (XRD) analysis

The mineral composition of the karst infilling samples was analyzed by X-ray diffraction (XRD) [17, 18]. The primary constituents are quartz, montmorillonite, and muscovite, with contents ranging from 35~43%, 32~39%, and 8~13%, respectively. The relatively high montmorillonite content is the principal cause of the swelling behavior of the karst infilling. The detailed XRD results are presented in Fig. 4.

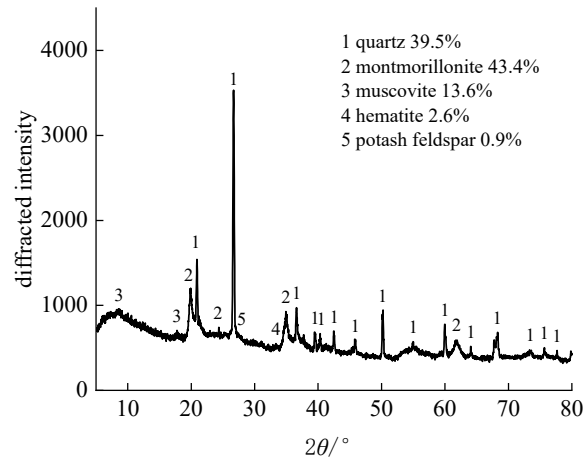


Fig. 4. XRD results of samples

2.4. TG Analysis

To further investigate the mineralogical characteristics of the karst infilling, thermogravimetric (TG) tests were performed, whereby the variation in interlayer water and structural water with increasing temperature was analyzed to reflect the mineral composition. The derivative thermogravimetric (DTG) curve was obtained by taking the first derivative of the TG curve. The steep decline stages in the TG curve correspond to the dehydration processes of the minerals and coincide with the peaks in the DTG curve. The TG and DTG curves derived from the experimental results are presented in Fig. 5.

Overall, the TG curve exhibits a stepwise decreasing trend. As the temperature increases from room temperature to approximately 200 °C, the adsorbed water in the soil is progressively released. A second decline stage in the TG curve occurs between 200 and 400 °C, which is attributed to the dehydration of interlayer water in montmorillonite. The DTG curve indicates that the mass loss rate gradually increases at the onset of interlayer water release and subsequently decreases once the dehydration is complete. A third decline stage appears between 400 and 750 °C, corresponding to the removal of structural water from montmorillonite. In this temperature range, the DTG curve also shows an initial increase followed by a decrease; however, the peak mass loss rate is lower and the variation is relatively gradual, signifying that the dehydration of montmorillonite is essentially complete. A further decline stage in the TG curve is observed between 750 and 900 °C, which is attributed to the dehydration of structural water in muscovite. These experimental results are largely consistent with the findings reported in Clay Minerals and Their Analysis [19, 20]. Therefore, the TG test results demonstrate that the karst infilling in the Jinan area exhibits distinct thermal characteristics of montmorillonite, further corroborating the XRD results.

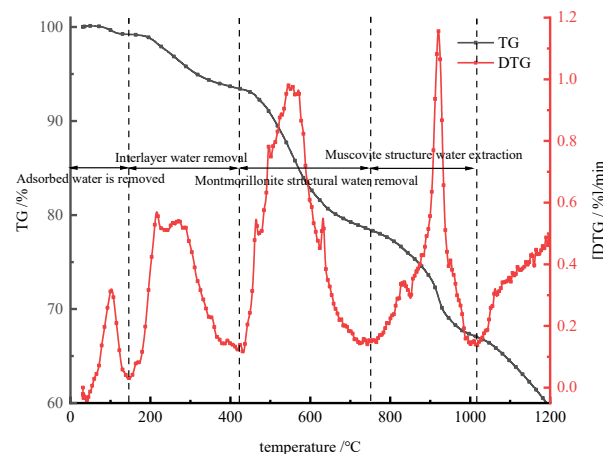


Fig. 5. TG test results of karst fillings

3. Dry-Wet Cycle Tests and Result Analysis

3.1. Subsection

To investigate the strength characteristics and microstructural evolution of the karst infilling under dry-wet cycles, unloaded swelling ratio tests, mercury intrusion porosimetry (MIP) tests, and consolidated undrained (CU) triaxial compression tests were

conducted. For the preparation of specimens subjected to dry-wet cycles, the collected karst infilling was first oven-dried, crushed, and passed through a 2 mm sieve. The sieved soil was then thoroughly mixed with an appropriate amount of distilled water to achieve the natural water content of 22.7%. The moistened soil was sealed in plastic bags and allowed to stand for 24 hours to ensure uniform moisture distribution. Based on the target dry density of 1.5 g/cm³, the soil was compacted into standard remolded triaxial specimens with dimensions of $\phi 39.1 \times 80$ mm using a specimen compactor for the triaxial and MIP tests. Specimens for the unloaded swelling ratio tests, with dimensions of $\phi 61.8 \times 20$ mm, were prepared by static compaction. Immediately after preparation, all specimens were sealed in plastic bags and stored at a constant temperature in the dark to prevent moisture loss.

3.2. Test Program

To simulate the dry-wet cycling conditions of the karst infilling, specimens were subjected to different numbers of artificial wetting and drying cycles. The specific procedure for one complete dry-wet cycle is as follows. The wetting process was carried out by vacuum saturation of the specimens in accordance with the Standard for geotechnical testing method (GB/T 50123-2019) [15]. The specimens were immersed in a saturation tank for 12 hours, after which they were oven-dried at a constant temperature for 12 hours. The upper limit of the drying temperature was determined with reference to historical meteorological data from the sampling site, and the oven temperature was set to 40 °C. A moisture content below 5% was defined as the dry state. Previous studies have indicated that the physical and mechanical properties of expansive soils tend to stabilize after 5 to 10 dry-wet cycles [21]. Accordingly, the condition with no dry-wet treatment was designated as zero cycles, and the subsequent tests were conducted at 1, 3, 7, and 11 cycles [22–24].

Unloaded swelling ratio tests were performed to evaluate the magnitude and variation pattern of the swelling behavior of the karst infilling specimens subjected to different numbers of dry-wet cycles. During the test, the specimen was placed in an unloaded swell test apparatus, and water was added after the dial gauge began recording, with the water level maintained at 5 mm above the top of the specimen throughout the test. The starting time of water addition was recorded, and the vertical swelling displacement was measured in real time using an automatic dial gauge. The test was terminated when the deformation of the specimen did not exceed 0.01 mm over a 6 hour period. The unloaded swelling ratio of the specimen was calculated using Equation (1):

This is example 1 of an equation:

$$\delta_t = \frac{Z_t - Z_0}{h_0} \times 100 \quad (1)$$

where δ_t is the unloaded swelling ratio at time t (%), Z_0 is the dial gauge reading at the beginning of the test, Z_t is the dial gauge reading at time t , and h_0 is the initial height of the specimen.

Mercury intrusion porosimetry (MIP) establishes the mapping relationship between the applied external pressure and the volume of mercury intruded based on the surface tension of mercury and its contact angle with the solid soil [25]. As the applied pressure increases, mercury can penetrate progressively smaller pores. The pore diameter corresponding to a given applied pressure can be determined using Equation (2), thereby characterizing the pore structure of the tested specimen.

$$P = \frac{4\sigma \cos \theta}{d} \quad (2)$$

where P is the applied pressure (kPa), σ is the surface tension of mercury, θ is the contact angle between mercury and the solid soil, and d is the diameter of the idealized cylindrical pore (μm). After undergoing a prescribed number of dry-wet cycles, the MIP specimens were air-dried at room temperature (25°C). The standard specimens were then trimmed into approximately cubical shapes with a volume of about 1 cm³. The mercury intrusion porosimeter, which was a MODEL PoreMaster 33 instrument used to determine the pore size distribution of the karst infilling after dry-wet cycles, was employed in this study.

Consolidated undrained (CU) triaxial compression tests were conducted to investigate the influence of dry-wet cycles on the mechanical properties of the expansive karst infilling. To prevent the generation of excess pore water pressure during consolidation and to precisely control the axial and lateral effective stresses, a constant loading rate was maintained throughout the test. The shear rate was set at 0.1%·min⁻¹, and the confining pressure was set at 150 kPa. The test was terminated when the stress–strain curve exhibited a distinct peak and an additional axial strain of 3% was applied beyond the peak. In cases where no distinct peak was observed, the test was terminated at an axial strain of 20%.

3.3. Characteristics of Unloaded Swelling Ratio

The results of the unloaded swelling ratio tests are presented in Fig.6. The variation trends of the unloaded swelling ratio with test time under different numbers of dry-wet cycles are generally consistent, all exhibiting a rapid increase stage, a gradual increase stage, and a stabilization stage. However, the stabilized unloaded swelling ratio values differ significantly among the specimens. The specimen not subjected to dry-wet cycles ($N=0$) reached a swelling ratio of 44%, which decreased to approximately 32% after 3 cycles and to approximately 12% after 11 cycles. As shown by the relationship curve between the number of dry-wet cycles and the unloaded swelling ratio in Fig. 8, the unloaded swelling ratio decreases rapidly in the initial stage of dry-wet cycling, changes slowly between 3 and 7 cycles, and then declines sharply thereafter.

It is evident that, although the unloaded swelling ratio of the karst infilling decreased to 27% of its initial value after 11 dry-wet cycles, indicating that dry-wet cycling can effectively mitigate its swelling potential, a residual swelling ratio of 12% still poses a certain degree of risk. It is anticipated that with a further increase in the number of dry-wet cycles, the karst infilling could degrade to a weakly expansive soil with low risk.

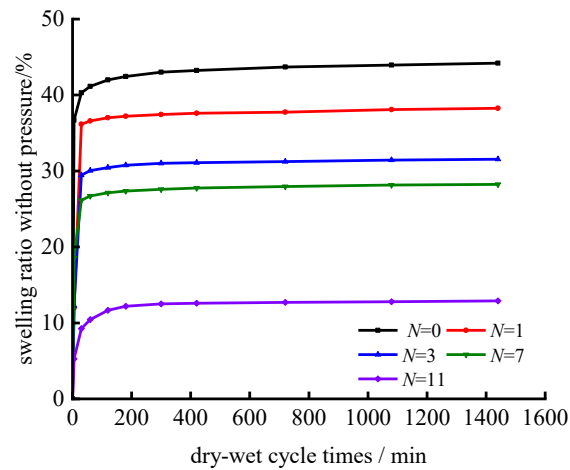
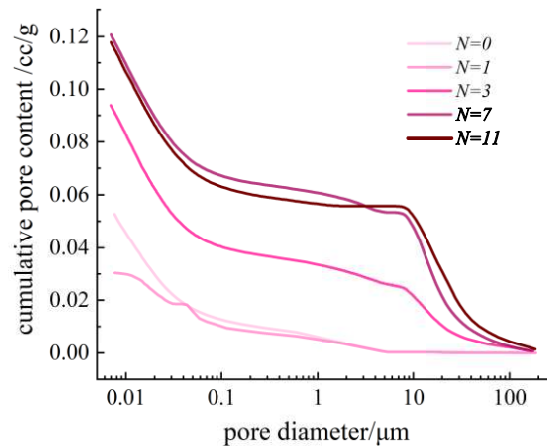


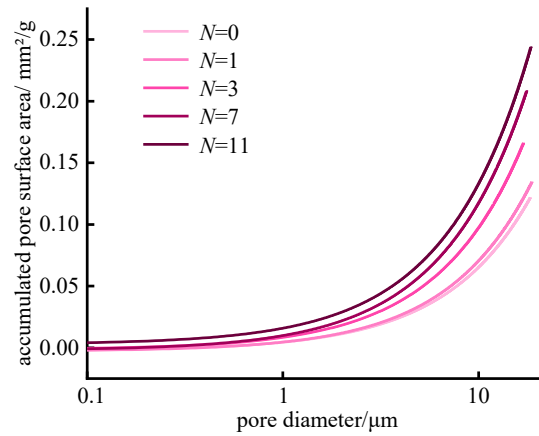
Fig. 6. Unloaded swelling ratio test results

3.4. Pore Characteristics

Fig.7(a) presents the cumulative pore volume curves of specimens subjected to dry-wet cycles, as determined by mercury intrusion porosimetry (MIP). It can be observed that the pore diameter distribution curve of the specimen without dry-wet cycling exhibits a gradually decreasing trend. With an increasing number of dry-wet cycles, the curves progressively develop a characteristic pattern of an initial decline, followed by a gentle intermediate segment, and then a steep decline. This indicates a marked increase in the content of pores larger than $10\ \mu\text{m}$, whereas the distribution of pores in the diameter range of $0.1\sim 10\ \mu\text{m}$ remains relatively consistent across different cycles. Meanwhile, the entire curve shifts upward with increasing cycle numbers, suggesting that dry-wet cycling leads to a significant increase in the total pore volume of the specimens.



(a)



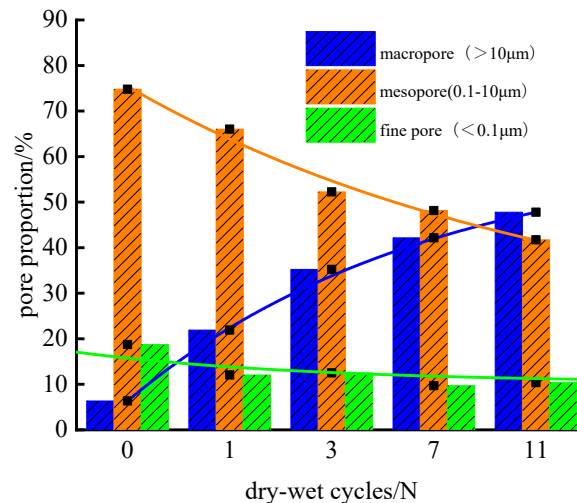
(b)

Fig. 7. Pore volume and pore surface area distribution under dry-wet cycles

(a) Pore volume distribution, (b) pore surface area distribution

By approximating the pores as spherical, the cumulative pore surface area was derived from the pore volume data, as shown in Fig.7(b), which illustrates the relationship between pore diameter and cumulative pore surface area under different numbers of dry-wet cycles. It can be observed that the cumulative pore surface area of the specimens increases progressively with the number of dry-wet cycles. The cumulative surface area begins to increase gradually when the pore diameter exceeds $1\mu\text{m}$, and exhibits an exponential increase as the pore diameter approaches and exceeds $10\mu\text{m}$, indicating that large-diameter pores exert a particularly pronounced influence on the total pore surface area. This irreversible change in pore structure results from the combined effects of repeated moisture ingress and egress, the progressive breakdown of interparticle cementation, and the initiation and propagation of microcracks.

According to the experimental data, the initial pore volume was 0.18 cm^3 , and it increased by 0.15 cm^3 after 11 dry-wet cycles. With reference to the pore size distribution of the soil specimens, pores with diameters greater than $10\mu\text{m}$ were defined as macropores, those smaller than $1\mu\text{m}$ as micropores, and those in the intermediate range as mesopores [26]. Fig.8 presents a histogram of the pore volume changes under dry-wet cycles. As can be seen from the figure, the proportion of macropore volume increases progressively with the number of dry-wet cycles, from merely approximately 6% in the untreated condition to 49% after 11 cycles. Correspondingly, the proportion of mesopore volume gradually decreases from 75% to 41% over the course of dry-wet cycle. The proportion of micropores remains relatively low throughout the process and generally exhibits a declining trend, decreasing from 19% to 10%. These changes in pore proportions indicate that the expansive karst infilling initially possesses a relatively dense structure with low porosity. Under repeated dry-wet cycles, the fine and compact clay minerals undergo recurrent swelling and shrinkage, which accelerates structural damage and loosening of the surrounding silt particles, leading to the coarsening and coalescence of small and medium-sized pores. As a result, the total pore volume increases by approximately 83%, and the macropore volume accounts for nearly half of the total porosity.

**Fig. 8.** The size distribution of pores under dry-wet cycles

3.5. Strength Characteristics

Based on the triaxial tests, the stress–strain relationships, stress path variations, and the relationships among strain, effective stress ratio, and pore water pressure were obtained for specimens subjected to different numbers of dry-wet cycles. Fig.9 presents the stress–strain curves of the expansive karst infilling under different numbers of dry-wet cycles. It can be observed that the deviatoric stress decreases markedly after just one dry-wet cycle and continues to decline with further cycling. When the number of cycles exceeds seven, the decrease in deviatoric stress tends to level off, indicating that the mechanical properties of the karst infilling gradually stabilize once the number of dry-wet cycles surpasses a certain threshold.

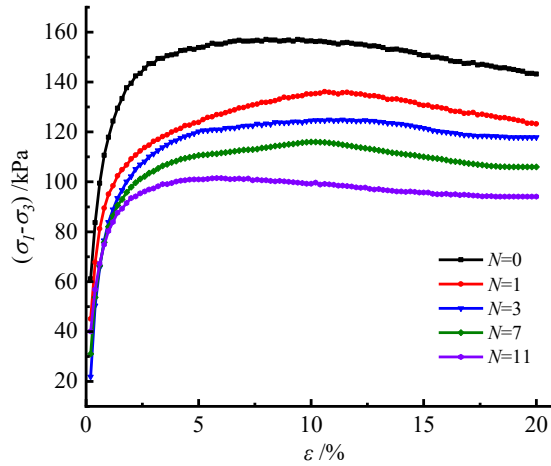


Fig. 9. Stress-strain relationship of samples under different dry-wet cycles

$$E = 8.24 \times e^{(-x/1.75)} + 12.97 \quad (3)$$

$$\tau = 57.56 \times e^{(-x/3.45)} + 99.14 \quad (4)$$

The fitted curves are shown in Fig.10. As the number of dry-wet cycles increases, the elastic modulus decreases, with a particularly pronounced decline in the initial stage, followed by a gradual stabilization between 3 and 11 cycles, exhibiting a trend of rapid decrease initially and a slower decline thereafter. This behavior can be attributed to the relationship between the elastic modulus and soil stiffness. dry-wet cycles lead to the rapid accumulation of initial damage, causing extensive development of internal fissures within the soil and a consequent reduction in stiffness, which is manifested as a substantial decrease in the elastic modulus during the first three dry-wet cycles. In the middle and later stages of dry-wet cycling, an internal fissure network has largely been established, and subsequent cycling primarily results in the gradual propagation of existing fissures and the formation of only a limited number of new ones. The effect on the overall stiffness is thus diminished, accounting for the slow decline in the elastic modulus during these stages.

In contrast, the shear strength exhibits a relatively uniform decline with increasing dry-wet cycles, showing a progressively decreasing trend overall. The shear strength is jointly governed by cohesion and the internal friction angle. Under repeated dry-wet cycles, the recurrent ingress of water dissolves cementing soils, leading to a sustained and irreversible decrease in interparticle bonding. Concurrently, the particle surfaces become rounded and the minerals softened, resulting in a gradual reduction of the friction coefficient and further weakening of frictional resistance. The continuous decline in shear strength also indicates that the chemical dissolution and physical wear induced by dry-wet cycles are progressive and irreversible processes.

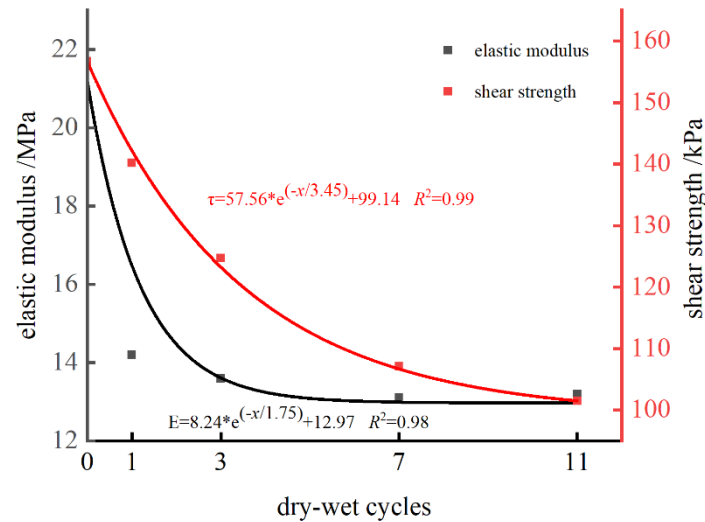


Fig. 10. The relationship between the number of dry-wet cycles and the elastic modulus and shear strength

The stress path in a triaxial test describes the continuous trajectory of the stress state evolution of a soil element during loading. The effective stress path curves under different numbers of dry-wet cycles are presented in Fig. 11. It can be observed that the stress paths of all soil specimens exhibit a transition from an initial linear segment to a curved segment, and the inflection point occurs progressively earlier as the number of dry-wet cycles increases. This phenomenon can be explained as follows: at the initial stage of the test, the specimen is in a dry state with relatively high stiffness, resulting in a linear stress path. When the stress level reaches a critical value (the inflection point), the soil deteriorates into a nearly saturated, weakened state. Beyond the inflection point, the stress path becomes horizontal or exhibits a descending trend, indicating that the soil has entered a strain-softening phase following plastic yielding. The more dry-wet cycles the specimen has undergone, the more severe the structural damage, leading to the increasingly earlier appearance of the inflection point.

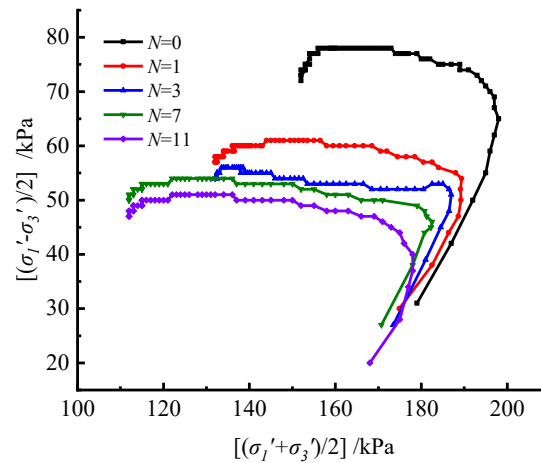


Fig. 11. The change of stress path under different dry-wet cycles

Fig. 12 presents the relationship curves between strain and effective stress ratio under different numbers of dry-wet cycles. As shown in the figure, the effective stress ratio of the specimen not subjected to dry-wet cycles ($N=0$) initially increases with strain and then tends to stabilize, exhibiting strain-hardening behavior. In contrast, for the specimens that have undergone dry-wet cycles, no distinct peak is observed in the curves; instead, the effective stress ratio approaches a plateau after reaching a certain value. This indicates that the soil specimens do not exhibit pronounced brittle failure, but rather undergo sustained deformation over a wide strain range and ultimately reach a relatively stable stress state, manifesting ductile failure behavior.

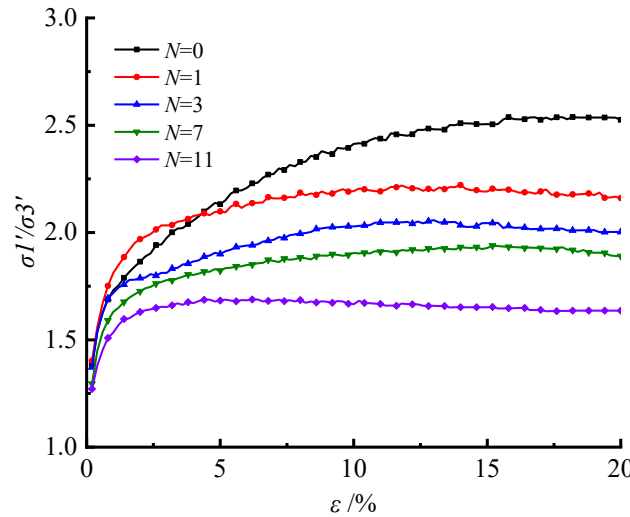


Fig. 12. Relationship between strain and effective stress ratio

Fig.13 illustrates the variation in pore water pressure with axial strain under different numbers of dry-wet cycles. As the axial strain increases, the pore water pressure of the specimen not subjected to dry-wet cycles ($N=0$) exhibits a continuous increase. This is because its structure is relatively intact, and under undrained conditions, the compressive potential energy released by structural damage consistently exceeds the inherent drainage capacity of the soil, resulting in a monotonic accumulation of pore pressure. With an increasing number of dry-wet cycles, the pore water pressure rises more rapidly in the early stage of shearing, while the rate of increase gradually diminishes in the later stage. This can be explained as follows: in the early stage, shear forces cause soil blocks to slide along weak planes and rapidly compress macropores, leading to a sharp short-term increase in pore pressure. In the later stage, as the soil enters a plastic state, the compressive potential energy and the energy dissipated through drainage reach equilibrium, and the pore pressure tends to stabilize. Meanwhile, the pore water pressure at a given strain level increases with the number of dry-wet cycles. From a microstructural perspective, both the total pore volume and the proportion of macropores increase under dry-wet cycling, and the repeated swelling and shrinkage progressively weaken the interparticle cementation. Consequently, during triaxial testing, soil particles become more susceptible to rearrangement and compaction, resulting in the generation of higher magnitudes of excess pore water pressure.

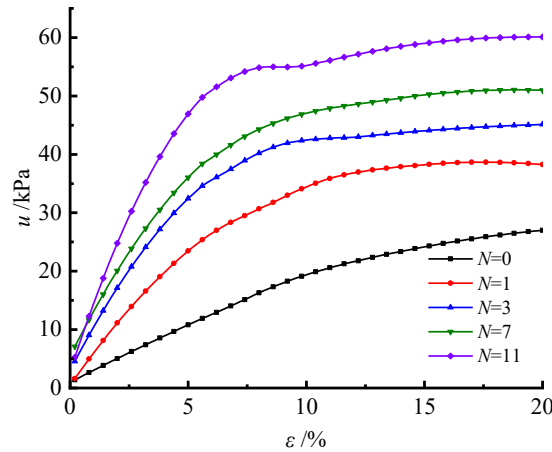


Fig. 13. Relationship between strain and pore water pressure

3.6. Mesoscopic Structure and Macroscopic Mechanical Properties Deterioration Mechanisms and Damage Evolution

The damage induced by dry-wet cycles to the karst infilling can be characterized by macroscopic parameters such as yield stress and elastic modulus, as well as by microscopic parameters including pore number, area, and volume [27].

Based on the deviatoric stress at failure obtained from triaxial tests, a macroscopic damage variable D_f for the karst infilling subjected to dry-wet cycles is defined, which can be calculated using the following equation [28]:

$$D_f = \frac{(\sigma_1 - \sigma_3)_{f,0} - (\sigma_1 - \sigma_3)_{f,N}}{(\sigma_1 - \sigma_3)_{f,0}} \quad (5)$$

where $(\sigma_1 - \sigma_3)_{f,0}$ is the deviatoric stress at failure for zero dry-wet cycles, and $(\sigma_1 - \sigma_3)_{f,N}$ is the deviatoric stress at failure after N dry-wet cycles. A larger D_f value indicates a greater extent of specimen damage. The D_f values and the corresponding curve obtained from the triaxial test results are presented in Fig. 14.

Based on the pore volume variation obtained from MIP tests, the change in the volume of macropores (diameter > 10 μm) was selected to reflect the microstructural damage characteristics, as these macropores are considered representative of fissure contributions. A microscopic damage variable D_m for the karst infilling subjected to dry-wet cycles is defined using the MIP test results, with the following calculation formula:

$$V_L = V_{cum} \times m \quad (6)$$

$$V_A = V_J + V_L \quad (7)$$

$$D_m = \frac{V_L}{V_A} \quad (8)$$

Where V_L is the fissure volume of the soil after testing, V_{cum} is the cumulative pore volume of the soil after testing, m is the mass of the soil, V_A is the total volume of the soil, and V_J is the matrix volume of the soil after testing. The D_m values and the corresponding curve obtained from the MIP test results are also presented in Fig. 14. both D_f and D_m increase rapidly during the initial stage of dry-wet cycling, indicating that the rapid increase in pore connectivity leads to a substantial loss of soil strength at this stage. In the later stage, the curves tend to level off, suggesting that the pore reorganization is largely complete and the strength deterioration approaches a limit.

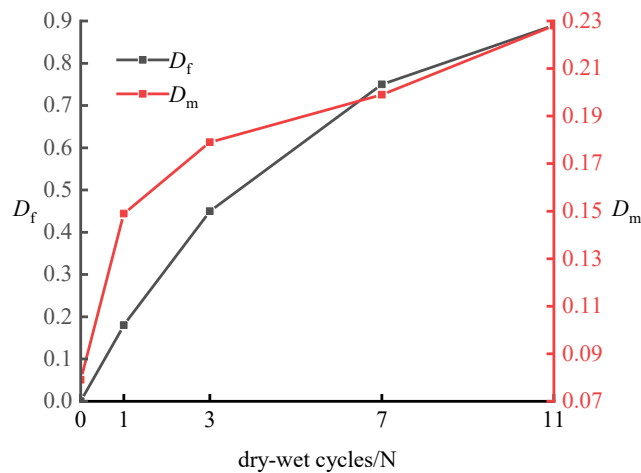


Fig. 14. Variation curve of macro and micro damage variables

To investigate the correlation mechanism between D_f and D_m in the macro-micro damage evolution, further analysis was conducted, yielding the fitting equation presented as Equation (9) and illustrated in Fig. 15.

$$D_f = 0.05e^{14D_m} - 0.14 \quad (9)$$

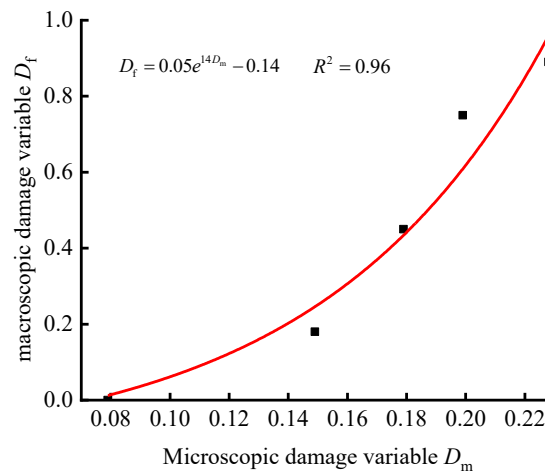


Fig. 15. Curve of macro and micro change rule

The macroscopic damage exhibits a nonlinear exponential increase with the growth of the microscopic variable representing crack propagation, indicating that microstructural pore evolution is the fundamental driving force behind the loss of macroscopic strength. Once the accumulated microstructural damage reaches a critical threshold, it triggers a pronounced strength deterioration response. This nonlinear relationship provides a correlative basis for characterizing the damage evolution of expansive karst infilling in the Jinan area. The macro-micro damage model predicts that when D_m exceeds the threshold value of 0.18, the permeability of the soil increases significantly, the fissure network develops at an accelerated rate, and the strength deterioration process intensifies, thereby necessitating timely engineering protective measures.

4. Conclusions

Taking the typical karst sites in Jinan as the engineering background, this study first identified the swelling characteristics and their underlying causes of the karst infilling. Subsequently, unloaded swelling ratio tests, mercury intrusion porosimetry (MIP) tests, and triaxial tests were conducted under dry-wet cycling conditions to investigate the evolution of mechanical properties and micro-structure, as well as the macro-micro deterioration mechanisms of the karst infilling. The main conclusions are as follows:

The typical karst infilling in the Jinan area exhibits medium swelling potential, which is attributed to its high montmorillonite content. dry-wet cycling can significantly reduce its swelling behavior.

dry-wet cycling leads to a continuous increase in the internal porosity of the karst infilling, with a pronounced tendency for small and medium pores to transform into macropores. The alteration of the pore structure is a key factor contributing to the degradation of the macroscopic mechanical properties.

dry-wet cycling causes the deterioration of the strength of the karst infilling. The breakdown of mineral cementation and pore reorganization result in a marked decrease in both the elastic modulus and the shear strength parameters. Concurrently, the deterioration of the pore structure induces particle rearrangement and compaction, leading to an increase in excess pore water pressure at a given strain and a reduction in effective stress, which causes the karst infilling specimens to transition from strain-hardening to strain-softening behavior.

The macroscopic damage characteristics of the expansive karst infilling under dry-wet cycles can be characterized by micro-structural pore evolution. A macro-micro damage relationship model was established based on the experimental data, which enables the prediction of the soil deterioration process and provides a reference for engineering construction in karst terrains in the Jinan area.

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References

1. Rabbi M, Bicalho K V. Matric suction evolution and shear strength variation of unsaturated expansive clays under successive drying-wetting cycles. *Soils and Foundations*, 58 (4):978-992 (2018). 346-348
2. Ozer A T, Isik N S. Influence of initial water content on shear behaviour of unsaturated expansive soil subjected to cyclic hydrothermal alternations. *Cold Regions Science and Technology*, 176:103042 (2020). 349-350
3. Nowamooz H, Masrouri F. Relationships between soil fabric and suction cycles in compacted swelling soils. *Engineering Geology*, 114:444-455 (2010). 351-352
4. Puppala A J, Pedarla A. Crack initiation and strength degradation of expansive soils under repeated wetting-drying alternations. *Journal of Materials in Civil Engineering*, 31 (9):04019197 (2019). 353-354
5. Fattah M Y, Al-Obaidi M J. Combined drying-wetting and freeze-thaw impacts on compressibility and hydraulic conductivity of high-plastic expansive clay. *Geomechanics and Engineering*, 30(2):167-178 (2022). 355-356
6. Sivapullaiah P V, Venkataraman L. Fly ash and plant fibre amendment for mitigating drying-wetting induced damage in expansive clayey soils. *Construction and Building Materials*, 390:131852 (2023). 357-358
7. Peron H, Hueckel T. Desiccation crack propagation in medium-swelling clays under variable wetting-drying boundary conditions. *Acta Geotechnica*, 16 (8):2541-2556 (2021). 359-360
8. Di Matteo A, Bigotti F. Mercury intrusion porosimetry investigation on pore damage of compacted expansive soil after cyclic wetting and drying. *Bulletin of Engineering Geology and the Environment*, 78 (6):4321-4335 (2019). 361-362
9. Ferber V, Auriol J C. Quantitative CT characterization of shrink-swell crack networks in expansive clays subjected to drying-wetting cycles. *Computers and Geotechnics*, 123:103598 (2020). 363-364
10. Nahlawi H, Kodikara J K. SEM-based microstructural evolution and aggregate swelling of expansive soils upon water immersion and cyclic drying. *Applied Clay Science*, 221:106487 (2022). 365-366
11. Albrecht B A, Benson C H. Effect of Desiccation on Compacted Natural Clays. *Journal of Geotechnical & Geoenvironmental Engineering*, 128(1):67-75 (2001). 367-368
12. Al-Homoud A S, Basma A A, Husein Malkawi A I, et al. Cyclic Swelling Behavior of Clays. *Journal of Geotechnical Engineering*, 121(7):562-565 (1995). 369-370
13. Nowamooz H, Masrouri F. Hydromechanical behaviour of an expansive bentonite/silt mixture in cyclic suction-controlled drying and wetting tests. *Engineering Geology*, 101(3-4):154-164 (2008). 371-372
14. Al-Mukhtar M, Khatlab S, Alcover J F. Microstructure and geotechnical properties of lime-treated expansive clayey soil. *Engineering Geology*, 139-140(none): 17-27 (2012). 373-374
15. GB/T 50123-2019; Standard for geotechnical testing method. China Planning Press: Beijing, China, (2019). 375
16. GB 50112-2013; Technical code for building in expansive soil area. China Architecture & Building Press: Beijing, China, (2013). 376
17. S. Feng, H. Xiao, L. Chen, Influence of nanosols on mechanical performance and microstructure of cement paste, *Constr. Build. Mater.* 509, 145146 (2026). 377-378
18. J. Lyu, J. Yang, C. Liu, X. Guan, J. Moon, S. Feng, J. Zhang, Z. Ge, H. Zhang. Effect of carbonation curing time during early age on mechanical and microstructural properties of cement-based soils incorporating superabsorbent polymers, *J. Build. Eng.* 120, 115464 (2026). 379-381
19. Bergaya F, Lagaly G. Handbook of Clay Science: Montmorillonite thermal analysis and mineralogical characterization [M]. Amsterdam: Elsevier (2013). 382-383
20. Zapata C E, Houston W N. Stabilization threshold of expansive soil properties after sequential wetting-drying cycles. *Journal of Geotechnical and Geoenvironmental Engineering*, 143 (11):04017084 (2017). 384-385
21. Buzzi O, Fityus S. Multiscale mechanical deterioration of high-plastic clays exposed to periodic moisture fluctuation [J]. *International Journal of Solids and Structures*, 193:266-278 (2020). 386-387
22. Pourakbar S, Huat B B K. Mechanical response variations of expansive soils under diverse wet-dry cyclic protocols. *KSCE Journal of Civil Engineering*, 27 (5):2089-2102 (2023). 388-389
23. Tang L, Cong S, Ling X, et al. A unified formulation of stress-strain relations considering micro-damage for expansive soils exposed to freeze-thaw cycles. *Cold Regions Science and Technology*, 153(SEP.):164-171 (2018). 390-391
24. Delage P, Cui Y J. Pore water retention and microstructural rearrangement of clays induced by cyclic drying and wetting. *Canadian Geotechnical Journal*, 61(3):412-425 (2024). 392-393
25. Giesche H. Mercury intrusion porosimetry for pore size characterization of geomaterials: principle and experimental correction. *Particle & Particle Systems Characterization*, 35 (9):1800125 (2018). 394-395

26. Kodikara J K, Sivakumar V. Pore classification criteria for compacted clays based on mercury intrusion results. *Geotechnical Testing Journal*, 43 (3):498-512 (2020). 396
397
27. Desai C S. Mechanics of porous media and continuum damage model for unsaturated compacted soils [M]. Boca Raton: CRC Press, (2019). 398
399
28. Voyiadjis G Z, Song Y. Definition of macroscopic damage variable from triaxial failure deviatoric stress for cyclically degraded geo- 400
materials. *International Journal of Damage Mechanics*, 30 (7):1012-1031 (2021). 401