Study on structural characteristics of expansive soil slope in transmission line engineering

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Abstract. Expansive soil has significant properties such as expansion and contraction, fracture and water strength attenuation, which leads to deformation and instability of expansive soil slope, which seriously threatens the safety construction and normal operation of transmission line towers along the line. The characteristics of expansive soil during drying-wetting cycles play an important role in slope stability analysis. Using shear tests and scanning electron microscopy tests, the changes in shear strength and microstructure characteristics of expansive soil were studied. The failure mode of expansive soil slopes under dry wet cycling was analyzed using Midas software. The research results indicate that the drying-wetting cycles have a significant impact on the cohesion of expansive soil, but have a small impact on the internal friction angle. As the number of drying- wetting cycles increases, the micro surface structure and surface-edge structure of expansive soil decrease, and the changes in the structure of expansive soil lead to a decrease in the strength of expansive soil. The slope failure mode is traction shallow failure.

Keywords: expansive soil; drying-wetting cycles; shear strength; microstructure; slope stability.

1 Introduction

Expansive soil is a special type of clay, mainly composed of hydrophilic clay minerals such as illite and montmorillonite. It has adverse engineering characteristics such as swelling shrinkage, cracking, and overconsolidation, and is widely distributed throughout the country. In addition, the strength characteristics of expansive soil are affected by the dry wet cycle of seasonal climate change, which can easily bring safety hazards to engineering construction in China. For a long time, many scholars have conducted extensive research on the changes in mechanical properties of expansive soil and its dry wet cycle conditions. Regarding the characteristics of expansive soil and its cracks, Yang Heping et al. [1-3] explored the mechanical properties of expan-

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sive soil in regions such as Nanning, Guangxi, Hami, Xinjiang, and Jingmen, Hubei through experiments; Zhang Jiwei et al. [4] [5] investigated the crack variation characteristics of expansive soil and its impact on slope stability. Regarding the development and evolution of cracks in expansive soil during dry wet cycles, Zhang Jiajun et al. investigated the characteristics of crack development and deformation mechanism of expansive soil during dry wet cycles [6-9], and Li Wei et al. conducted further quantitative research on this [10]. In addition, Hu Xuhui et al. investigated the deformation law of expansive soil under different wet dry cycle conditions [11]; Mohamed Abubaker Ahmed Mohamed Salih et al. improved the mechanical properties of expansive soil by using disintegrating sandstone and cement [12] [13], while Devkota Bikash et al. conducted in-situ monitoring of expansive soil slopes [14], and conducted beneficial explorations on the monitoring and treatment of expansive soil slopes.

This article takes an transmission line expansive soil slope in South China as the research object, and obtains its basic physical parameters through geotechnical tests. By conducting indoor shear tests, stress-strain curves and mechanical parameters were obtained. Combined with scanning electron microscopy (SEM) tests, the microstructure characteristics of the soil were obtained. Finally, numerical simulation software was used to analyze the failure mechanism of expansive soil slopes under wet dry cycles.

2 Indoor testing

2.1 Experimental soil and sample preparation

Expansive soil is a kind of highly plastic clay rich in hydrophilic minerals and easy to exhibit water absorption and expansion characteristics, and the strength of expansive soil has obvious variability. In order to explain the microscopic mechanism of expansive soil's water absorption and expansion and water loss shrinkage at the microscopic level by exploring the evolutionary characteristics of expansive soil strength under the effect of dry and wet cycling. The expansive soil used in this test is taken from the middle section of the Nanling Mountain Mountains, with a depth of 2m. The natural soil is brownish yellow in color, dense in texture, and has not been significantly disturbed at the depth of sampling. The free expansion rate is 51%. According to the Technical Specification for Building in Expansive Soil Areas, the test soil is weak expansive soil, and the other physical and mechanical properties are shown in the table below (Table 1). Thoroughly crush the retrieved expansive soil after natural air drying and pass it through a 2mm sieve. When adding ingredients, weigh the sieved soil material and spread it layer by layer on an iron tray. Spray an appropriate amount of distilled water on the surface of the loose soil and mix thoroughly. Then seal the sample for 48 hours to allow the moisture in the soil material to fully diffuse. The initial dry density of the sample is 1.50g \/cm3. In order to make the expansion and contraction crack morphology of the sample more obvious, the initial moisture content is designed to be 18%. Weigh an appropriate amount of prepared soil material and slowly compact it using static pressure method, with a compaction rate controlled at 2mm/min, until the weighed soil material is completely pressed into the mold.

Table 1. Statistical Table of Soil Physical and Mechanical Parameters

Proportion	Liquid limit ω_L/%	Plastic limit ω_P/%	Max Dry density g/cm^3	Best Moisture content
2.69	47.82	27.78	1.69	25.3%

2.2 wetting-drying test

According to the expansive soil sample taken on site, its moisture content was measured to be 17.1%, and this moisture content of 17% was used as the initial control point for wet dry cycles. If the moisture content of the soil is within 5%, it is considered dry soil. Considering that the on-site conditions cannot be completely dry, the moisture content of 5% is determined as the lowest control point for the wet dry cycle amplitude. At the same time, the moisture content of 35% when the sample is saturated is determined as the highest control point for the wet dry cycle. Finally, the wet dry cycle amplitude of 5%~35% is determined as one wet dry cycle. Take out the dry soil sample, add water to prepare it into a sample with a moisture content of 35%. (Use a spray bottle to continuously spray water into the acrylic box in 5 times until the water completely seeps into the soil, and then proceed with the next spray.) After preparation, place it into a 15cm (length), 10cm (width), and 4cm (height) acrylic box. Then, place it in an oven to dry the soil sample until the moisture content is 5%. This is a wet dry cycle process. When the moisture content of the soil sample reaches 17%, it is taken out with a ring cutter to obtain a direct shear ring cutter soil sample after one dry wet cycle. The same steps are used to take out soil ring cutter samples with 2-5 dry wet cycles and conduct direct shear tests on the soil sample after 2-5 dry wet cycles. Under each wet dry cycle, vertical stresses of 50kPa, 100kPa, 200kPa, and 300kPa were applied to a total of 20 specimens. Measuring the shear strength parameters of soil using ZJ strain controlled direct shear apparatus.

3 Test results and Analysis

3.1 Changes in mechanical strength

The relationship between the shear strength of soil and the number of wet dry cycles is shown in Figure 1. The number of wet dry cycles has a significant impact on the shear strength of expansive soil. After 1-2 cycles of wet and dry cycles, the shear strength of the soil significantly decreases; After experiencing 3-5 cycles of wet and dry cycles, the shear strength of the soil gradually tends to stabilize.

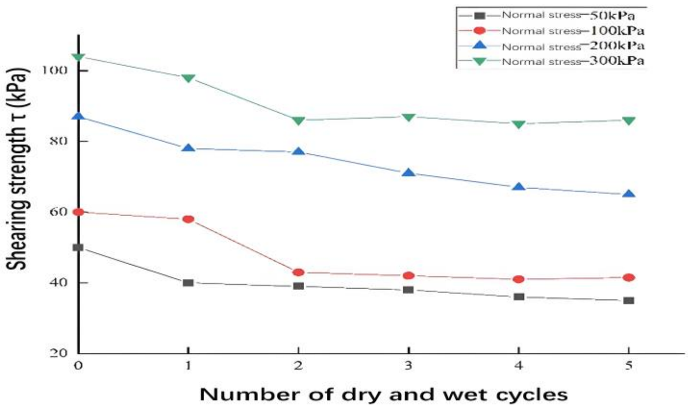


Fig. 1. The variation of shear strength with the number of drying-wetting cycles

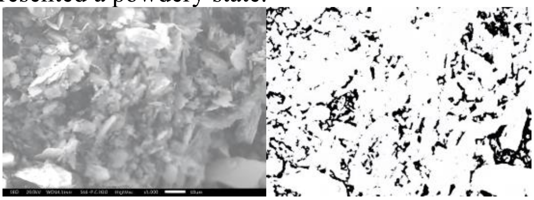
The cohesive force of expansive soil gradually decreases with the increase of dry wet cycles, and the degree of attenuation gradually decreases under a single cycle, with an overall attenuation of 62.1% after 5 dry wet cycles. The dry wet cycle has little effect on the variation of internal friction angle strength. As the dry wet cycle progresses, the internal friction angle of the soil is basically at a stable value, with an overall attenuation of 8.05% after 5 dry wet cycles. Based on the influence of changes in the number of wet dry cycles on soil cohesion and internal friction angle, it is found that the decrease in shear strength of expansive soil after undergoing wet dry cycles is mainly due to the decrease in soil cohesion.

3.2 Development of fissures (pores)

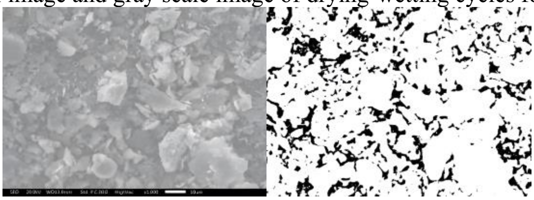
Observe the development of soil cracks after different wet dry cycles. When the number of wet dry cycles is 1, only a small number of cracks are generated on the surface of the soil. As the number of wet dry cycles increases, the cracks expand from the surface to the deep; When the number of wet dry cycles is 2, cracks begin to appear inside the soil, and a large number of pores develop inside the soil. The development of pores inside the soil will cause a decrease in the strength of the soil, which explains the phenomenon that the shear strength of the soil in Figure 1 also decreases to a large extent after 2 wet dry cycles; After three cycles of wet and dry cycles, the soil produced a large number of horizontal and vertical cracks, which crisscrossed and penetrated each other, reducing the overall stability of the sample; When the number of wet dry cycles is 5, a large number of cracks penetrate through it.

3.3 Scanning electron microscopy test

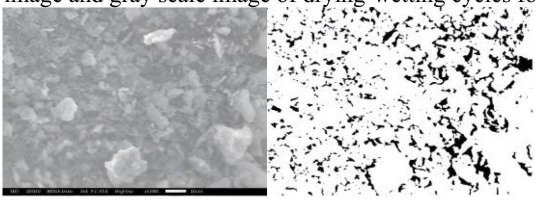
Perform electron microscopy scanning tests (1000 times) on expansive soil samples under different wet dry cycles to obtain high-definition grayscale images of the microstructure of expansive soil. Select images with clear and distinct features for research and analysis, and use ImageJ to quantitatively analyze the porosity of expansive soil. Surface to surface connected polymer is the most common structural form of expansive soil, which has greater water loss shrinkage and water absorption expansion ability compared to aggregate structure. According to the scanning electron microscopy (SEM) image of the initial soil sample, it can be seen that the surface particles of the initial expansive soil sample mostly present a sheet-like structure with strong overall integrity, and the flocculent structure is widely distributed. The particles inside the expansive soil are mostly overlapped and aggregated in the form of edge surface and surface surface connections, forming a relatively dense morphology. According to the SEM image of the expansive soil after 1-5 cycles of wet and dry cycles shown in Figure 2, the soil is mainly composed of flat and sheet-like particles. After the first to second wet dry cycles, the expansive soil particles mainly exhibit a sheet-like structure, and after the third to fifth wet dry cycles, they mainly exhibit sheet-like and clumpy structures. As the number of wet dry cycles increases, the flocculent structure formed by the aggregation of sheet-like particles decreases, the overall integrity of the soil structure is lost, and the degree of dispersion is stronger. After one cycle, the particles inside the soil are overlapped and aggregated in the form of edge surface and surface surface connections, forming a relatively dense morphology. After two cycles, a significantly larger single particle was formed in the soil sample, and the particle size decreased with the increase of cycles. The structure was mainly composed of stacked granular particles and gradually became loose. After the fourth wet dry cycle, it presented a powdery state.



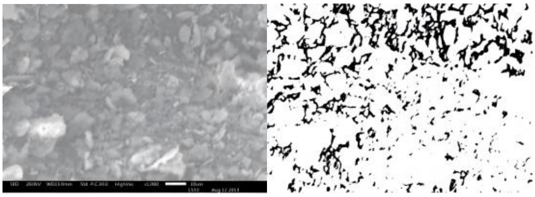
(a) SEM image and gray scale image of drying-wetting cycles for 1 time



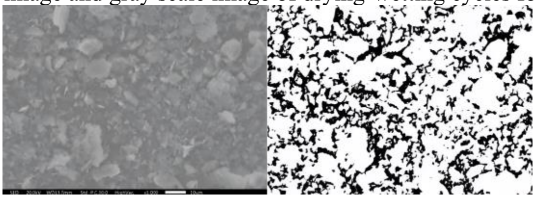
(b) SEM image and gray scale image of drying-wetting cycles for 2 times



(c) SEM image and gray scale image of drying-wetting cycles for 3 times



(d) SEM image and gray scale image of drying-wetting cycles for 4 times



(e) SEM image and gray scale image of drying-wetting cycles for 5 times

Fig. 2. SEM and gray scale images after different drying-wetting cycles (with a magnification of 1000 times)

3.4 Scale distribution of particles and pores

The classification of soil porosity generally falls into two categories: macropores and micropores. The former refers to the open spaces between aggregates, while the latter pertains to the internal pores within aggregates. Porosity is commonly measured using methods such as mercury intrusion porosimetry and image processing, covering scales ranging from several nanometers to a few hundred micrometers. In this study, employing Image J image software for precise extraction of porosity characteristic parameters, the porosity distribution in expansive soil is categorized into four levels: macropores (diameter D > 5μm), mesopores (2μm < D < 5μm), micropores (1μm < D < 2μm), and nanopores (D < 1μm).

From Table 2, it can be observed that under different cycles of wetting and drying, the distribution of pore sizes in expansive soil samples varies. The percentage content of macropores (D > 5μm) within the soil structure exceeds 80%, followed by mesopores (D ranging from 2μm to 5μm).

Table 2. Changes in porosity of expansive soil with the number of drying-wetting cycles

Number of dry and wet cycles	Total porosity Rate (%)	D>5μm （%）	2μm<D<5μm （%）	1μm<D<2μm （%）	D<1μm （%）
1	14.94	12.37	1.47	0.47	0.63
2	16.17	14.08	1.15	0.53	0.42
3	13.41	11.05	1.29	0.51	0.56
4	15.51	12.98	1.22	0.77	0.55
5	12.63	10.21	1.27	0.64	0.50

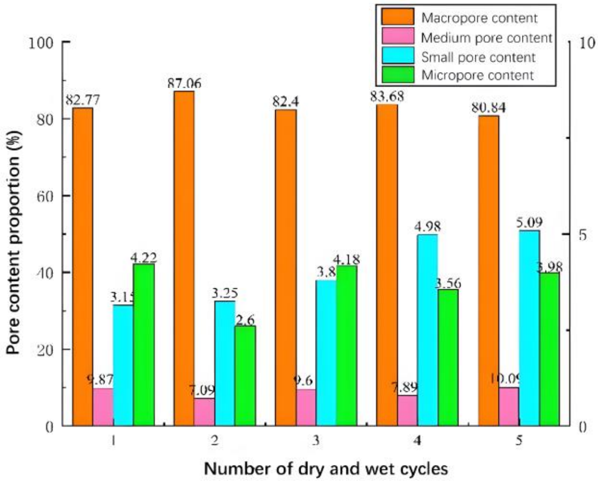


Fig. 3. The proportion of pore content changes with drying-wetting cycles

According to Figure 3, as the number of wet dry cycles increases, the content of mesopores gradually decreases, and mesopores play a bridging role in the evolution of the entire pore parameter characteristics. When the number of wet dry cycles is 1-2, the content of mesopores significantly decreases, which also indicates that the change of mesopores leads to a change in the shear strength of expansive soil; When the number of wet dry cycles is between 3 and 5, the content of mesopores tends to stabilize. According to the scanning electron microscopy images of 1-5 wet dry cycles, when the wet dry cycle is 1, the expansive soil particles are mainly in the form of flakes and clumps, and the clay particles inside the soil sample are mostly stacked in the form of surface to surface and surface to edge, forming a dense morphology; When the number of wet dry cycles is 3-5, the internal structure of the expansive soil is generally similar. The larger single particles become smaller during the 3-5 wet dry cycles, and the dispersion of the soil structure is stronger. The flocculent structure gradually decreases during this process. The soil is mainly composed of flat and sheet-like particles, and there are more obvious single particles distributed in the soil sample, but the particle size is smaller. The structure is also mainly composed of stacked granular particles, and the structure is relatively loose.

4 Analysis of Slope Stability under Dry Wet Cycle

Establish an accurate geological 3D model based on geological data. Using Midas numerical simulation software to analyze the displacement, plastic zone, and maximum shear strain increment distribution of expansive soil slopes, comprehensively analyze the specific reasons for slope failure, and then analyze the failure mode of expansive soil slopes under dry wet cycles.

4.1 Calculation model and parameters

As shown in the figure, the terrain map is imported into Midas software to select the research area and generate a three-dimensional geological model. The mesh type is a mixed mesh (mainly hexahedron), with a thickness of 5 meters for expansive soil and below it is bedrock. Among them, the thickness of gravel rock is 10 meters, and the calculation model is 160 meters long and 140 meters wide. A total of 62309 nodes and 61672 units are divided. Adopting the Mohr Coulomb criterion, which can describe the instability mechanical response of rock and soil under shear, and using roller support around the three-dimensional calculation model, only constraining its normal displacement; Apply fixed boundary conditions (no displacement allowed) at the bottom, and use free boundary conditions for the upper slope. The material parameter values are shown in Table 3.

4.2 Calculate operating conditions

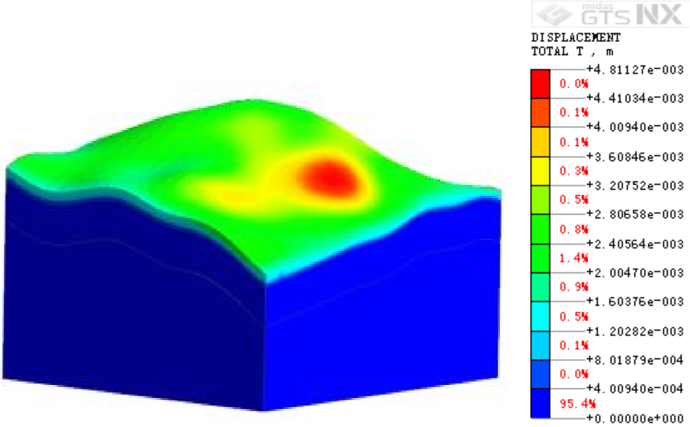
Simulate the stability analysis of expansive soil slopes under 1-5 cycles of dry and wet cycles, with each cycle divided into dry season and rainy season. During the rainy season, simulate the saturation state of the ground surface, and use spatial functions to set the water level in three-dimensional space on GTSNX.

Table 3. Physical and Mechanical Parameters of Materials

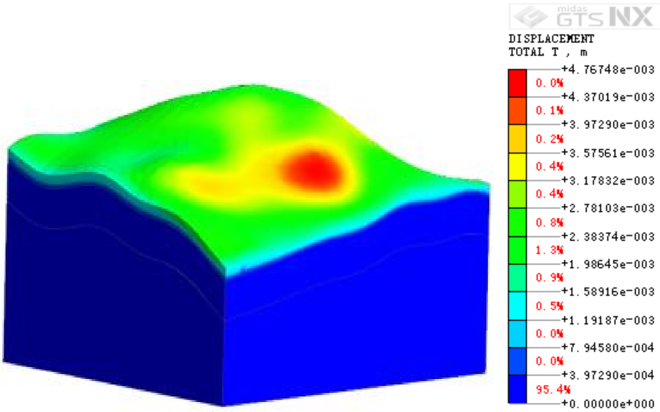
Material	Elasticity modulus (MPa)	Poisson's ratio	Density (kg/m3)	Cohesion (MPa)	Internal friction Angle (°)	Number of dry and wet cycles
Expansive soil	0.1	0.30	1690	0.0312	14.5	1
				0.0243	14.0	2
				0.0219	14.1	3
				0.0201	13.8	4
				0.0187	13.7	5
Glutenite	5	0.25	2300	25	40	
Limestone	6	0.25	2500	30	42	

4.3 Analysis of calculation results

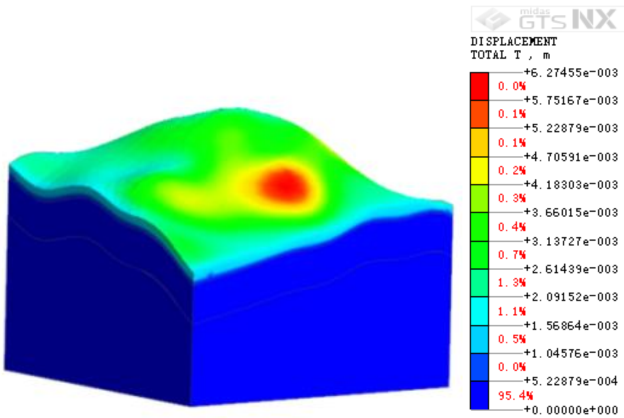
According to the numerical simulation results shown in Figure 4, the maximum displacement of the slope is located at the shoulder, in a raised state. When the number of wet and dry cycles is 1 and 2, the maximum deformation of the slope is 4.8cm and 4.7cm, respectively, and the overall stability of the slope is maintained; During the fourth wet dry cycle, the overall displacement of the slope suddenly increased, with a maximum deformation of 14.8cm. At this time, the slope was in an unstable state, with a stability coefficient of 0.97. When the number of wet dry cycles was 5, the maximum deformation of the slope was 17.6cm, and the slope was also in an unstable state, with a stability coefficient of 0.93. The influence of the number of wet dry cycles on the overall displacement of the slope is shown in Table 4.



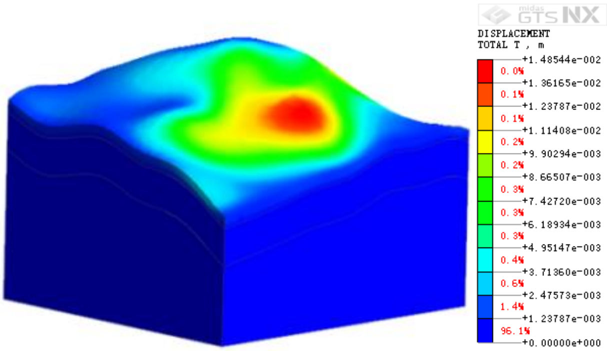
(a) Overall deformation characteristics of slope after the first drying-wetting cycle



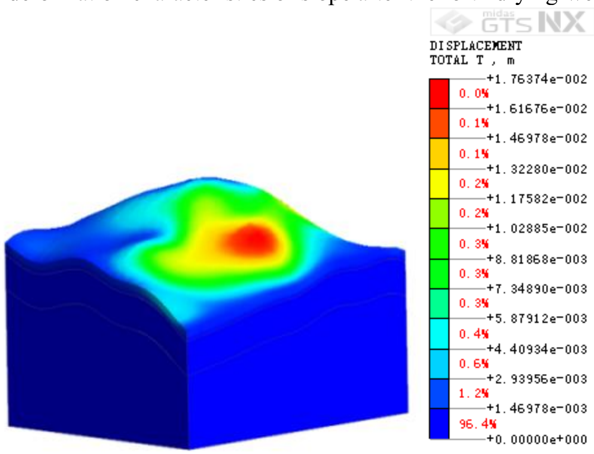
(b) Overall deformation characteristics of slope after the second drying-wetting cycle



(c) Overall deformation characteristics of slope after the third drying-wetting cycle



(d) Overall deformation characteristics of slope after the forth drying-wetting cycle



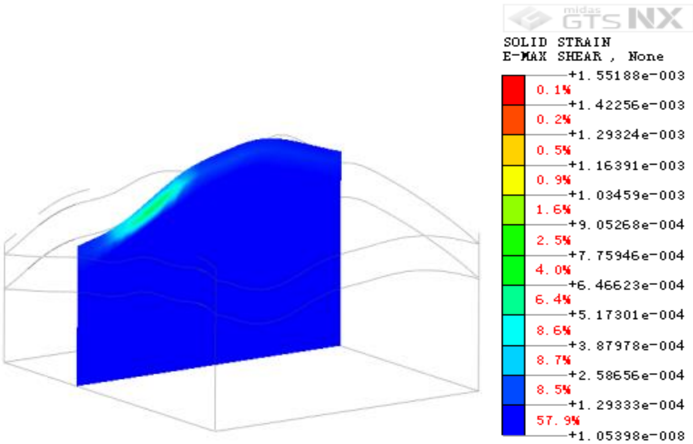
(e) Overall deformation characteristics of slope after the fifth drying-wetting cycle

Fig. 4. Overall deformation characteristics of expansive soil slopes after drying-wetting cycles

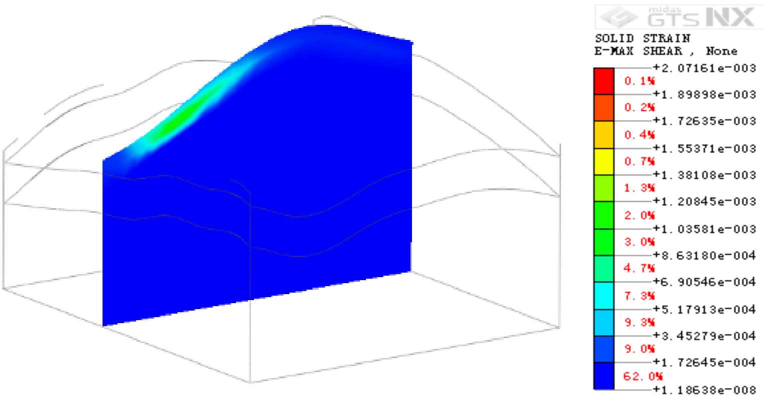
Table 4. Influence of drying-wetting cycles on slope displacement

Number of cycles	1	2	3	4	5
Maximum displacement（cm）	4.8	4.7	6.3	14.8	17.6

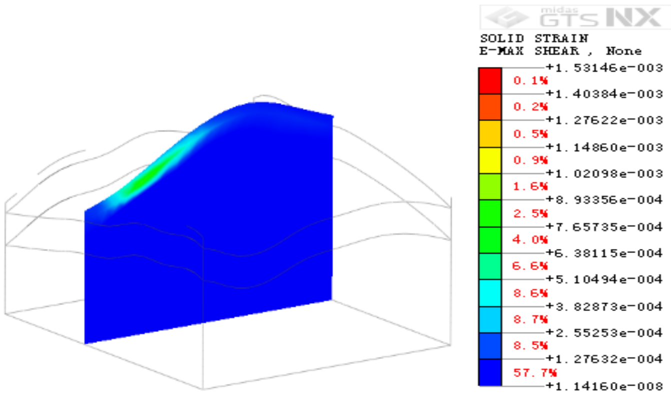
The maximum shear strain distribution of the slope during 1-5 wet dry cycles is shown in Figure 5. From the calculation results, it can be seen that when the number of wet dry cycles is 1, the maximum increase in shear strain occurs at the foot and shoulder of the slope, and the distribution range is relatively small; When the number of wet dry cycles is 2-3, the range of maximum shear strain concentration gradually increases, and the distribution of maximum shear strain has not yet penetrated, and the slope is still in a stable state; When the wet dry cycle is 4, the maximum shear strain area gradually penetrates, and the slope is in an unstable state.



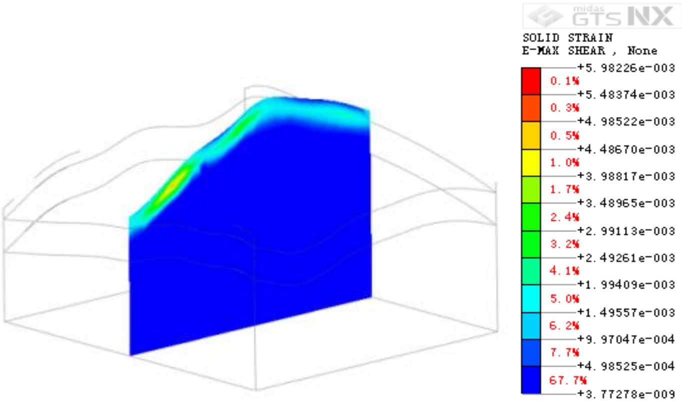
(a) Distribution characteristics of maximum shear strain of slope after the first drying-wetting cycle



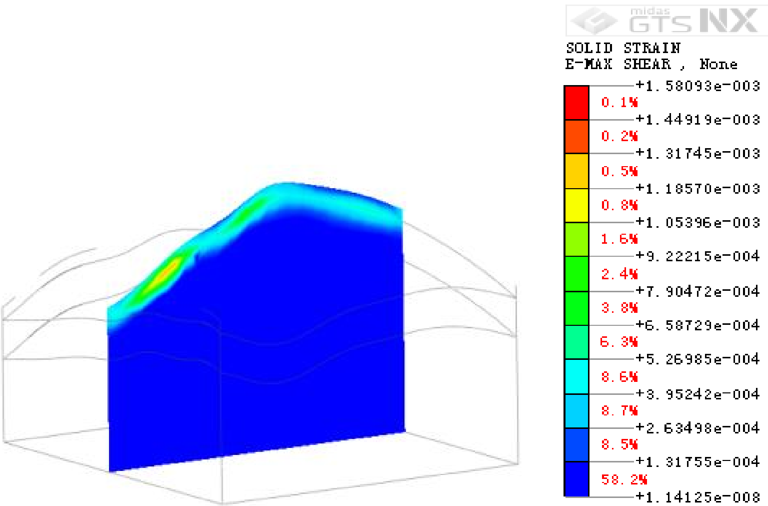
(b) Distribution characteristics of maximum shear strain of slope after the second drying-wetting cycle



(c) Distribution characteristics of maximum shear strain of slope after the third drying-wetting cycle



(d) Distribution characteristics of maximum shear strain of slope after the forth drying-wetting cycle



(e) Distribution characteristics of maximum shear strain of slope after the fifth drying-wetting cycle

Fig. 5. Distribution characteristics of maximum shear strain of slope after drying-wetting cycles

According to the numerical simulation results, it can be seen that the slope is in a stable state as a whole when the number of wet and dry cycles is 1-3. When the number of wet and dry cycles is 4, the stability coefficient of the slope becomes 0.97, making the slope in an unstable state. At the same time, from Table 5, it can be seen that the fourth wet and dry cycle causes the maximum displacement increment of the slope to suddenly increase, which also proves that the slope is unstable at this time. The relationship between the number of wet dry cycles and the stability coefficient is shown in Table 5. According to the calculation results of slope stability coefficient, it can be seen that as the number of wet dry cycles increases, the overall displacement of the slope continues to increase. After the fourth wet dry cycle, the slope becomes unstable and fails. After the shallow collapse at the foot of the slope, the upper soil loses its support and subsequently experiences traction sliding. Figure 6 shows the failure mode diagram of the slope. The unstable sliding surface of the slope is located at the junction of expansive soil and gravel, and is tangent to the bottom of the expansive soil layer. Under the action of dry wet cycles, cracks first appear inside the expansive soil layer of the slope, which deteriorates the strength of the soil. The sliding surface first appears at the foot of the slope. With the increase of dry wet cycles, the transverse and longitudinal cracks of the slope develop and connect, and the sliding surface gradually penetrates from the foot of the slope to the top of the slope. From the results of scanning electron microscopy experiments, it can be seen that during the gradual process of wet dry cycles, the overhead pore structure between larger aggregates gradually changes, and the surface to surface structure and surface deformation structure also gradually decrease, resulting in a gradual decrease in the content of large pores and an increase in the content of small pores; From the results of the wet dry cycle test, it can be seen that during this process, the cracks inside the soil gradually increase, causing changes in the soil structure and leading to a decrease in the shear strength of the soil.

Table 5. Effect of drying-wetting cycles on slope stability coefficient

Number of cycles	1	2	3	4	5
Stability coefficient Fs	1.45	1.23	1.04	0.97	0.93

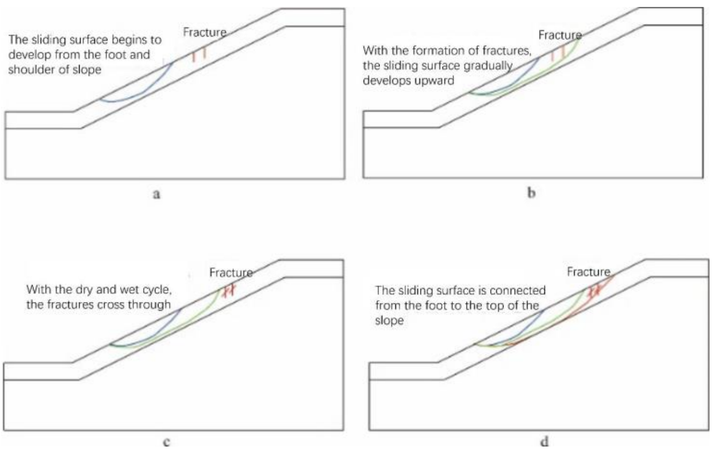


Fig. 6. Failure mode diagram of expansive soil slope

5 Conclusions

(1) By taking slope soil samples on site and conducting geotechnical and wet dry cycle tests, it was found that the number of wet dry cycles mainly affects the sh

ear strength of expansive soil by affecting its cohesion. During the wet dry cycle, the cracks inside the expansive soil gradually increase, the crack width gradually widens, and the pores gradually increase, resulting in a decrease in soil strength.

(2) Through scanning electron microscopy experiments, the microstructure characteristics of expansive soil were analyzed. As the number of wet and dry cycles increased, the pore structure of expansive soil changed significantly. From the perspective of microstructure, the changes in pore size distribution characteristics showed a decrease in macropores, an increase in micropores, and a gradual decrease in surface surface and edge structures during wet and dry cycles, These two structures control the overall strength of expansive soil, and as the dry wet cycle progresses, it leads to a decrease in these two structures, resulting in a decrease in soil strength.

(3) Through numerical simulation of expansive soil slopes under different wet dry cycles, it was found that the stability coefficient of the slope gradually decreases with the increase of wet dry cycles. The overall failure mode of the slope is shallow traction failure, and the deformation of the slope mainly starts from the position of the foot and shoulder of the slope. As the dry wet cycle continues, the deformation of the slope gradually develops to the top of the slope, and finally the deformation zone gradually penetrates, causing traction sliding of the slope.

(4) This paper mainly focuses on the swelling and shrinking characteristics of expansive soil under the action of dry and wet cycles, but the influence of annual temperature, precipitation and other factors on the swelling and shrinking of expansive soil cannot be fully reflected. Therefore, the swelling and shrinking characteristics of expansive soil under different circulation modes need further research in theory and practice.

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