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WATER IMMERSION DEFORMATION OF UNSATURATED AND COMPACTED LOESS

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We studied the relationship of humidifying deformation and water immersion content from the unsaturated to the saturated states and analyzed the factors influencing humidifying deformation in water immersion of compacted loess. Humidification axial strain was mainly affected by deviatoric stress, and the influence was significant. We studied the deformation characteristics of compacted loess under water immersion using a CT-triaxial wetting collapsibility test system. Our test results demonstrate that under certain environmental conditions, changes in water content may cause wetting deformation, which exhibits a large impact on the structural characteristics of soil samples. A relationship between the initial state of water content and the water content state under constant stress was established. The results demonstrated that the expression characteristics of humidification level parameters were consistent with the evolution characteristics of structural parameters. This provides a basis for the establishment of a soil strain damage model and quantitative structural indexes.

Introduction

Compacted loess is a common foundation material in the loess gully region. It is widely used in filled soil engineering features such as foundations, roadbeds, and earth dams. The structure of loess changes greatly during excavation, transportation, and rolling compaction. Under compaction, the resistance between the loess solid particles is overcome and the amount of air and water between the solid particles is reduced. Compaction causes the movement and rearrangement of soil particles, which reduces soil porosity. This improves the strength and water stability of the soil. However, the processes of construction, rainfall infiltration, or groundwater level migration can cause wetting deformation. In large engineering projects, such as earth-rock dams, there can be humidification deformation problems in the fill. This can happen even when the compaction coefficient is greater than 0.90 and when the material is gravel, sandy gravel, or clayey soil. Thus, humidification deformation has a great influence on the deformation stability, cracking, and seepage stability of the fill [1-3].

The humidification deformation of soil refers to the deformation caused by the breakage, slippage, and rearrangement of particles in the framework of the soil structure. This is due to factors such as the softening of granular minerals in the water and the water lubrication between particles under stress conditions. Most of the research on soil humidification deformation involves coarse grained rockfill and uses the saturated humidification test, unsaturated humidification test, and dry-wet circulation humidification test [4]. Axial lateral limit compression or triaxial compression tests are often used for

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testing [5]. Test results analysis includes data on axial strain and volumetric strain of rockfill under different confining pressures, saturation, compactness, and stress levels [6].

In compacted loess with fine particles, strength loss and deformation failure can also occur after immersion in water. In large-scale construction, the loess fill can be destroyed due to humidification deformation under water immersion [7]. High-pressure consolidation instruments have been used to study the compression deformation of compacted loess under high pressure and lateral constraints in the process of humidification and dehumidification. High-pressure consolidation instruments have also been used to analyze the stress-strain relationship of compacted loess under different degrees of compaction and initial water content [8]. Furthermore, the variance analysis method has been used to analyze the relationship between deformation and matric suction during humidification and the final deformation effect of the loading path and water immersion path [9, 10]. A triaxial test system was used to study the deformation characteristics of compacted loess under different dry densities under stress and humidification by controlling confining pressure and matric suction [11, 12].

Most of the humidification deformation tests of loess only focused on the humidification deformation of soil in a natural state to a fully saturated state under stress action [11-13]. These tests ignored the relationship between soil humidification deformation and water content change and did not accurately reflect soil deformation under more complex water immersion conditions. In practical engineering applications, most of the soil does not reach a saturated state after humidification, and the process by which soil goes from a unsaturated state to a saturated state is time consuming. During this process, the soil is in a complex state of stress and strain.

Experiment on Humidification Deformation

The compacted Lishi loess Q2 in the Shaanxi Province (China), was studied. The relative density of the loess was 2.72, the plastic and liquid limits – 17.3% and 31.1%; the initial water content – 11.6% and the water content of the configured sample – 18.6%. Specimen dimensions were 39.1 mm diameter and 80 mm high.

The CT-triaxial wetting collapsibility test system of the Logistical Engineering University was used to measure volumetric strain, control the deviatoric stress, and measure the internal structure of the soil specimen dynamically, quantitatively, and nondestructively [13].

Two groups, each with 16 immersion tests, were evaluated in this study. Eight immersion tests with a dry density of 1.52 g/cm^3 and eight tests with a dry density ρ_d = 1.69 g/cm^3 were examined for matric suction ($u_a - u_w$) at 150 and 300 kPa, net confining pressure ($\sigma_3 - u_a$) at 50 and 100 kPa, and deviatoric stress ($\sigma_1 - \sigma_3$) at 100 and 200 kPa (σ_1 and σ_3 are the large and small principal stresses; u_a and u_w are the pore air and pore water pressures).

The test process was divided into two parts: the deviatoric stress consolidation stage and the water immersion stage under the conditions of controlling the matric suction. During the tests, the net confining pressure, deviatoric stress, and matric suction were controlled as constants, and the specimen was drained and consolidated until the deformation and displacement were stable. At the end of consolidation, the gas pressure was discharged to a zero level. At the same time, the confining pressure was lowered to maintain a stable net confining pressure. From the bottom of the specimen with a constant head pressure of water immersion until the discharge was equal to the amount of immersion, the specimen wetting deformation was stable. The immersion pressure was adjusted according to the degree of difficulty of specimen immersion. The confining pressure and the immersion pressure were simultaneously increased to ensure that the net confining pressure remained unchanged.

Analysis

The initial test stage was the consolidation process. During consolidation, both deviatoric stress and matric suction had significant effects on specimen displacement, and the net confining pressure had a lesser effect on displacement. The dry density was higher and the axial strain was smaller after stable

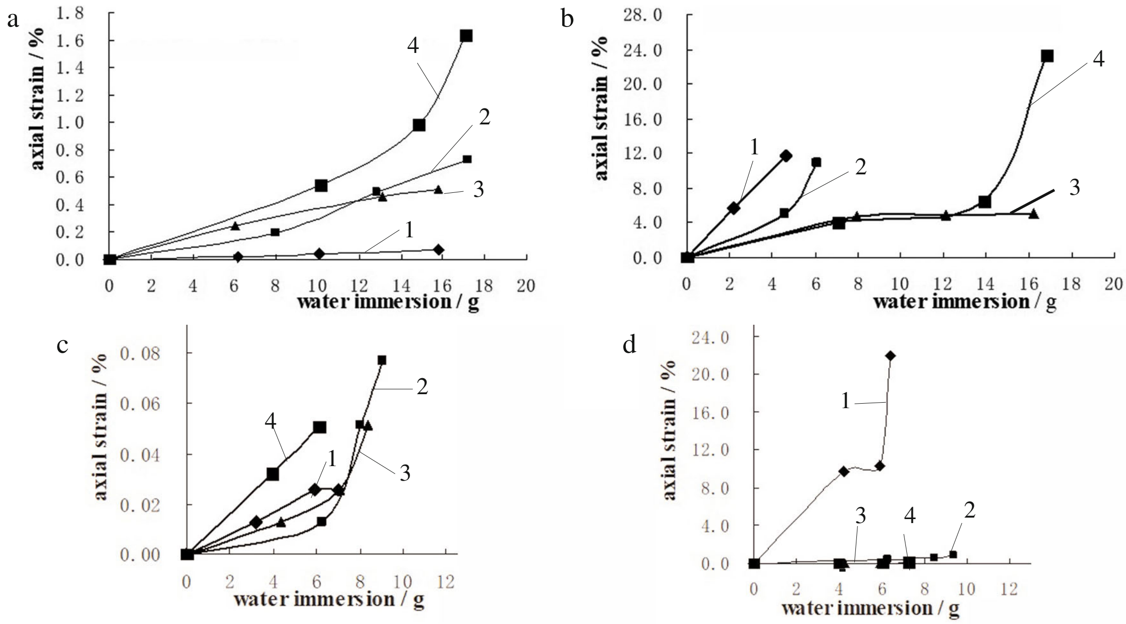

Fig. 1. Curves of axial strain with water immersion: a) ρ_d = 1.52 g/cm^3, $\sigma_1 - \sigma_3$ = 100 kPa; b) ρ_d = 1.52 g/cm^3, $\sigma_1 - \sigma_3$ = 200 kPa; c) ρ_d = 1.69 g/cm^3, $\sigma_1 - \sigma_3$ = 100 kPa; d) ρ_d = 1.69 g/cm^3, $\sigma_1 - \sigma_3$ = 200 kPa; 1) $\sigma_1 - u_a$ = 50 kPa, $u_a - u_w$ = 150 kPa; 2) $\sigma_1 - u_a$ = 50 kPa, $u_a - u_w$ = 300 kPa; 3) $\sigma_1 - u_a$ = 100 kPa; , $u_a - u_w$ = 150 kPa; 4) $\sigma_1 - u_a$ = 100 kPa, , $u_a - u_w$ = 300 kPa.

consolidation. During the consolidation process, only one specimen's axial strain reached 3.38% under the following conditions: dry density 1.52 g/cm^3, net confining pressure 50 kPa, matric suction 300 kPa, and deviatoric stress 200 kPa. Under other test conditions, the axial strain was < 1%. The following is an analysis of the changes of axial deformation and volumetric strain in the process of water immersion.

The immersion humidification test results show that the curves of axial strain $\Delta\varepsilon_1^w$ with water immersion m_w changed in the process of triaxial immersion humidification under different dry densities and deviatoric stress values (Fig.1a, b).

Figures 1c and 1d show the relationship between the axial strain of compacted loess and the amount of water immersion under a dry density of 1.52 g/cm^3 and deviatoric stresses of 100 and 200 kPa, respectively. The numerical value of axial strain in Figs. 1a and 1b show that axial strain is affected by the level of deviatoric stress. The greater the deviatoric stress, the greater the axial strain. Under the same deviatoric stress level, the humidifying deformation of the specimen under high confining pressure was larger than that under low confining pressure. The immersion amount was less affected by deviatoric stress. Based on the water content test, the water content of the specimen reached > 90% in Fig. 1b except for specimens No. 1 and No. 2. The final amount of water immersion mainly depends on soil compactness. The small net confining pressure and large deviatoric stress applied to specimens No. 1 and No. 2 produced bulging deformation during the immersion process (Fig. 1b). The axial strain value developed rapidly, and therefore the test was stopped. The final saturation degree of the specimens was 71.1% and 68.8% for specimens No. 1 and No. 2, respectively, and they did not reach the saturation state.

Figures 1c and 1d show the relationship between the axial strain of compacted loess and the amount of water immersion under a dry density of 1.69 g/cm^3 and respective deviatoric stresses of 100 and 200 kPa. The final saturation degree of each specimen was > 93% after immersion. The axial strain of specimens with a dry density of 1.69 g/cm^3 was greater than that of specimens with a dry density of 1.52 g/cm^3.

Figure 1d shows that only the No. 1 specimen was destroyed due to a small net confining pressure and large matric suction and deviatoric stress. The remaining specimens were not destroyed. Due to

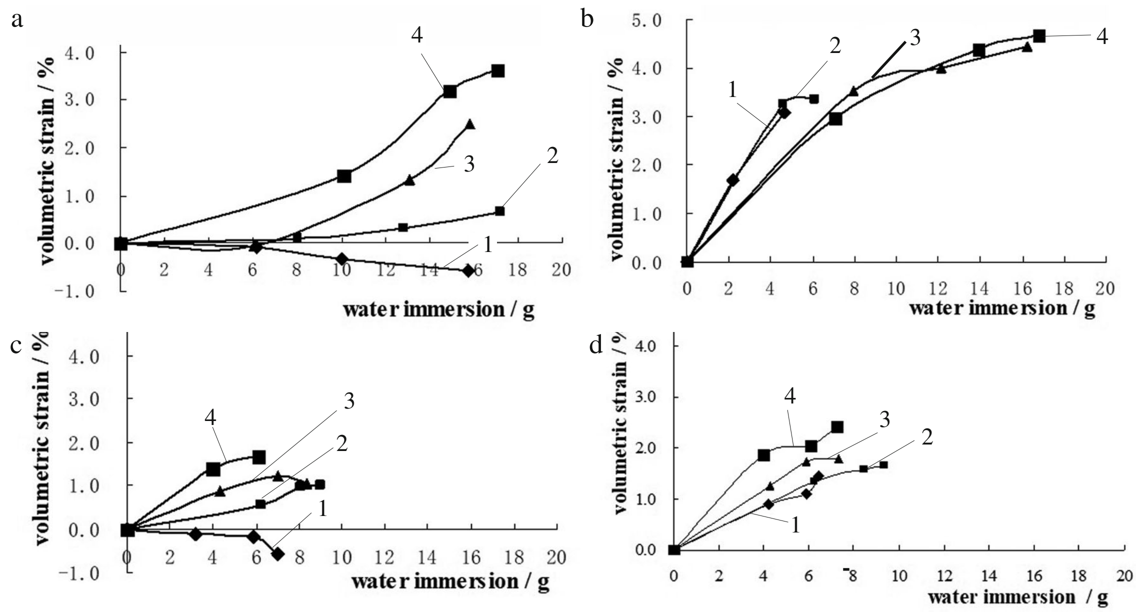

Fig. 2. Curves of volumetric strain with water immersion: a) $\rho_d = 1.52$ g/cm^3, $\sigma_1 - \sigma_3 = 100$ kPa; b) $\rho_d = 1.52$ g/cm^3, $\sigma_1 - \sigma_3 = 200$ kPa; c) $\rho_d = 1.69$ g/cm^3, $\sigma_1 - \sigma_3 = 100$ kPa; d) $\rho_d = 1.69$ g/cm^3, $\sigma_1 - \sigma_3 = 200$ kPa; 1) $\sigma_1 - u_a = 50$ kPa, $u_a - u_w = 150$ kPa; 2) $\sigma_1 - u_a = 50$ kPa, $u_a - u_w = 300$ kPa; 3) $\sigma_1 - u_a = 100$ kPa; , $u_a - u_w = 150$ kPa; 4) $\sigma_1 - u_a = 100$ kPa, , $u_a - u_w = 300$ kPa.

the large degree of specimen compaction, the axial strain reached 0.24% after consolidation and stability. With water immersion, the saturation degree of the specimens increased continuously, the axial strain increased rapidly, and the samples were destroyed by the wet shear action.

The volumetric strain measurement of specimens in the process of water immersion was examined by the high-precision volume variable measurement device of the CT-triaxial wetting collapsibility test system. Under stress and water immersion, the specimen exhibited dilatancy and shear shrinkage because of the greater distance between its component particles. Immersion humidification altered the change curves of volumetric strain $\Delta\varepsilon_1^w$. Water immersion m_w changed in the process of triaxial immersion humidification under different dry densities and deviatoric stresses (Fig. 2).

Figure 2 shows the relationship between the volumetric strain of compacted loess and the amount of water immersion with dry densities of 1.52 and 1.69 g/cm^3 and deviatoric stresses of 100 and 200 kPa. When the net confining pressure, matric suction, and deviatoric stress were small, only No. 1 specimens with dry densities of 1.52 and 1.69 g/cm^3, respectively, exhibited dilatancy, and the remaining specimens showed shear shrinkage. Their volumetric strain reached 0.58%. When the dry density and other conditions were the same, the net confining pressure was higher, and the volumetric strain was greater. For the specimens with larger matric suction, the strain of the specimen changed greatly after they were immersed in water. This was due to the larger amount of water discharged in the consolidation process and the resultant lower water content. Dry density, net confining pressure, matric suction, and deviatoric stress all had effects on the volumetric strain of specimens. However, the larger the net confining pressure, the smaller the influence of matric suction on specimen humidification deformation. The relationship curve of the volumetric strain caused by water immersion is more concentrated.

Relationship Between Humidification Level and Structural Parameter

Based on the water immersion tests for compacted loess, we found that the index of water immersion reflects the water content of the soil but does not reflect the soil humidification and deformation. Therefore, humidification level was introduced as a process variable to describe the state of soil humidification deformation and moisture content. It is also used to analyze the relationship between humidification level and the matric suction, deviatoric stress, net confining pressure, and dry density of the soil specimen [16].

Humidification level S_w is the ratio between the current change value of soil water content and the maximum possible change value of soil water content:

$$S_w = \frac{w_i - w_0}{w_s - w_0}, \tag{1}$$

where S_w is between 0 and 1. When the soil has a natural water content and is at a saturated state, 0 and 1 are taken respectively; w_i is the current water content of the soil, w_0 is the initial water content of the soil, and w_s is the saturated water content of the soil.

During the humidification process, with the development of loess humidification deformation, w_s changes constantly with the degree of soil compactness:

$$w_s = \left(\frac{\rho_w}{\rho_{dP}} - \frac{1}{d_s}\right) - \frac{\delta_u^P \rho_w}{\rho_{dP}}, \tag{2}$$

where ρ_{dP} is the dry density of the specimen after loading and deformation stabilization, ρ_w is the density of water, d_s is the relative density of the soil, and is the amount of deformation under the action of equivalent humidification stress *P*.

Substituting Eq. (2) into Eq. (1), S_w can be obtained as

$$S_w = \frac{w_i - w_0}{\left(\frac{\rho_w}{\rho_{dP}} - \frac{1}{d_s}\right) - \frac{\delta_u^P \rho_w}{\rho_{dP}} - w_0}, \tag{3}$$

where $w_i - w_0$ is the change in soil water content, δ_u^P is the deformation of soil during the humidification process.

After the soil specimen has reached a stable state of consolidation under a certain stress level, increasing the applied pressure or increasing the water content of the specimen can lead to increased or strength failure. Our test results demonstrate that water immersion acts as an equivalent to additional load. The water content change is converted into the equivalent pressure caused by humidification deformation, and the effect of humidification on soil specimens is equivalent to the effects of stress. The humidification level S_w describes the relationship between the strain produced by the process of soil immersion and the water content state. Equation (3) shows that the process state variables of soil from an unsaturated state to a near-saturated state can be calculated. The introduced process variable establishes an effective relationship between the water content and the humidifying stress of soil under the condition of constant stress.

The structural characteristics of the soil are described by a quantitative parameter that links the meso-structure and the macroscopic mechanical behavior. The representative parameters of the dynamic changes of the two aspects can then be incorporated into a unified mechanical model.

During the water immersion process of compacted loess, soil specimens showed structural changes under the action of net confining pressure, deviatoric stress, and matrix suction. To describe structural damage and evolution in the water immersion process, the structural parameter *m*, based on CT data, was introduced [17]. CT data was obtained by using medical Computerized Tomography detection technology to establish the relationship between rock-soil density and the X-ray absorption coefficient. This can reflect the image characteristics of the entire process of rock-soil material internal structural change:

$$m = \frac{M_f - M_i}{M_f - M_0}, \tag{4}$$

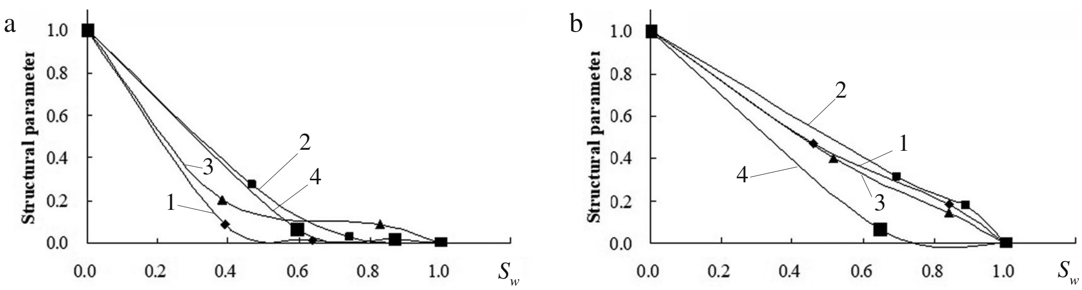

Fig. 3. Curve of structural parameter m versus humidification level S_w when deviatoric stress is 100 kPa: a) ρ_d = 1.52 g/cm^3; b) ρ_d = 1.69 g/cm^3; 1) $\sigma_1 - u_a$ = 50 kPa, $u_a - u_w$ = 150 kPa; 2) $\sigma_1 - u_a$ = 50 kPa, $u_a - u_w$ = 300 kPa; 3) $\sigma_1 - u_a$ = 100 kPa; , $u_a - u_w$ = 150 kPa; 4) $\sigma_1 - u_a$ = 100 kPa, , $u_a - u_w$ = 300 kPa.

where M_0 is the CT data of the sample before immersion, M_f is the CT data of the sample at the end of the immersion, and M_i is the CT data of the sample during the immersion process.

In the process of water immersion of compacted loess, curves of the structural parameters   versus changing humidification level variables S_w are shown in Fig. 3.

The structural parameter m of soil gradually decreased under water immersion, and the degree of reduction was affected by the soil humidification level S_w. As S_w increased, the original structure changed from a stable state to a failure state, and the saturated state of the soil changed from an unsaturated state to a saturated state. When the dry density, net confining pressure, and deviatory stress were the same, specimens with larger matric suction had lower water content after consolidation, and the original structure was preserved. The structural parameters were large, and after water immersion the humidification level and the specimen's volumetric strain increased. The range of structural parameter change was also larger. Therefore, the humidification level expression was consistent with the evolution of the structural parameters.

Conclusions

1. Under the triaxial water immersion test conditions in this study, dry density, net confining pressure, matrix suction, and deviatoric stress all had strong effects on the humidification deformation characteristics of compacted loess. As dry density increased, humidification deformation decreased. When the net confining pressure was small, the deviatoric stress and matric suction were large, and the specimens were easily destroyed. As net confining pressure increased, the effect of matric suction on the humidification deformation decreased.

2. During soil humidification, axial strain was affected by deviatoric stress. Deviatoric stress was positively correlated with the level of the axial strain. Humidification deformation under high confining pressure was greater than under low confining pressure. The total amount of immersion was less affected by deviatoric stress. When the net confining pressure, matric suction, and deviatoric stress were small, the specimen exhibited dilatancy. When the net confining pressure was large, the matric suction and deviatoric stress were small, and the specimen gradually changed from a small amount of dilatancy to shear shrinkage. When dry density and other conditions were the same, the net confining pressure was greater and the volumetric strain was greater.

3. Our test results demonstrate that, under certain environmental conditions, changes in water content in soil samples could cause wetting deformation, which has a large impact on the structural characteristics of soil samples. If the humidification constitutive relation of compacted loess soil could be determined, the relationship between the water immersion level and equivalent stress could be established. By introducing the levels of the humidification process, the relationship between the deformation of soil in the process of water immersion as well as the state of the water content could be described.

The effective relationship between the water content and the strain of the soil mass under the conditions of constant stress was established. The expression of the humidification level was consistent with the characteristics of the structural parameters, and these provided a basis for the establishment of a soil strain damage relation model and structural quantitative index.

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