Article

Time-Dependence of the Mechanical Behavior of Loess after Dry-Wet Cycles

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Abstract: The structure, time-dependent mechanical deformation, and strength characteristics of loess, which is loose and porous with well-developed vertical joints, are greatly affected by the dry-wet cycles, which are attributed to periodic artificial irrigation, rainfall, and water evaporation. To better understand the creep characteristics of loess under the effect of dry-wet cycles, Q_2 loess samples obtained from the South Jingyang County, China, were subjected to different dry-wet cycles (0, 5, 10, 15, 20) and sheared in triaxial creep tests. The experimental results revealed that: firstly, the maximum value of the deviatoric stress corresponding to creep failure gradually decreases with an increase in the dry-wet cycles. Secondly, the long-term strength of the loess after dry-wet cycles were obtained through the Isochronous Curve Method. It is found that the long-term strength and the number of dry-wet cycles showed an exponential decreasing relationship. In addition, the creep damage mechanism of loess due to dry-wet cycles is proposed. This study may provide the basis for understanding the mechanical behavior of the loess under the effect of dry-wet cycles, as well as guidelines for the prevention and prediction of loess landslide stability.

Keywords: loess; dry-wet cycles; triaxial creep test; creep behavior; strain-time; long-term strength

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1. Introduction

Loess is a weakly cemented loose sediment with a special material composition, which is widely distributed in the Loess Plateau of China (Figure 1) [1,2]. Creep phenomenon is common in loess-covered areas, and the creep characteristics of loess pose an important impact on the landslide formation and the construction of engineering structures [3–5]. The creep properties of loess vary due to the change of the environment. For example, unsaturated loess soils are usually subjected to wetting because of the natural rainfall or artificial irrigation, and loess soils would then be subjected to a drying process, i.e., water evaporation, as rainfall or irrigation stops. Such a process could be called a dry-wet cycle [6,7] and leads to the following consequences: the loss of soluble salts in the loess [8–10], the deterioration of the mechanical properties of the loess [11,12], and the change of shear strength, deformation, and permeability of the loess [13–15]. Therefore, the creep deformation of the loess was aggravated, which will contribute to the formation of disasters such as landslides.

The influence of dry-wet cycles on the time-dependent behavior of rocks has been considered in some research [16–19], while in the last few years increasing attention has been paid to experimental research into the behavior of loess soils. It is acknowledged that the reduction in the shear strength of the loess due to the dry-wet cycles is obvious [3,20,21]. Malusis et al. [22] reported that the hydraulic conductivity of the soil gradually increases as the number of dry-wet cycles increases. Until now, extensive attempts have been made on the physical and mechanical properties of loess after dry-wet cycles by using the uniaxial tensile shear test [23], direct shear test [24,25], the uniaxial compressive test [26],

conventional triaxial test [7,27], the soil-water characteristic curve (SWCC) of loess [28], etc. For example, Yuan et al. [23] carried out an experimental study on the tensile strength of the intact loess samples under dry-wet cycles and concluded that the repeated dry-wet cycle destroys the original structure of the intact loess and causes its tensile strength to disappear. Furthermore, Mu et al. [24] investigated the shear characteristics of loess samples under dry-wet cycles through direct shear tests and pointed out that the shear strength of loess gradually decreased as the number of dry-wet cycles increase. By conducting experiments, Li et al. [26] reported that the unconfined compressive strength, elastic modulus, and cohesive force of the loess specimen decreased with an increase in the number of dry-wet cycles, while the vertical compressive strain and failure deformation increased. Hu et al. [27] conducted triaxial tests considering three influence factors such as dry density, dry-wet cycle amplitude, and the lower bound water content of dry-wet cycles and established a compacted loess deterioration model (CLDM). Wang et al. [29] explored the effect of the dry-wet cycle on the collapsible deformation characteristics of compacted loess, and the results revealed that the compressive strain at all levels of deviatoric stress of specimens with different initial density gradually increases with the increase of the number of dry-wet cycles. The higher the initial compaction degree, the more significant effect of the dry-wet cycle on the mechanical behavior of compacted loess.

Figure 1. The study area.

The studies above have been focused on the variation in conventional mechanical properties such as shear strength, uniaxial tensile strength, uniaxial compressive strength, and triaxial shear strength of the loess after the dry-wet cycles. However, very little

attention has been paid to the damaging effect of the dry-wet cycles on the creep properties of loess. Additionally, a few experimental results have shown that the creep strains of loess soils developed after dry-wet cycles are not negligible [30] and can reach a critical value, eventually triggering loess landslides. In this backdrop, typical loess samples obtained from South Jingyang, China, were used to conduct triaxial creep tests under different numbers of dry-wet cycles to gain full insight into the time-dependent characteristics of loess soils and the deterioration of the long-term strength caused by dry-wet cycles. Furthermore, the damage mechanism of the creep characteristics of loess due to the dry-wet cycles is explored. This study would be beneficial for understanding the time-dependence of mechanical behaviors of loess soils as well as the long-term stability of loess slopes.

2. Triaxial Creep Tests

2.1. Sampling Site and Dry-Wet Cycle Process

The loess samples used in test were collected from the back scalp of the Dabuzi landslide in Jingyang County, Shaanxi Province (Figure 1). The sampling site was about 20 m from the edge of the platform, and the collected samples were identified as Lishi loess (Q2) according to previous studies [31]. The loess in this area have suffered from different degrees of dry-wet cycles as a result of the long-term repeat rise and fall of the groundwater level due to the farmland irrigation (Figure 2a) [32]. Therefore, the mechanical properties of loess deteriorates, resulting in the occurrence of the Dabuzi landslide (Figure 2b). All loess samples were firstly sealed and kept in iron buckets. Then, samples were brought back to the laboratory and cut immediately to a cylindrical specimen with a diameter of 61.8 mm and height of 125 mm. The procedures based on the ASTM standards were conducted to determine the index properties, namely Atterberg limits [33], specific gravity and density [34], and moisture content [35]. The basic physical index properties of loess are listed in Table 1.

Figure 2. The sampling site. (a) Irrigation canal, (b) landslide boundary.

Table 1. The physical index properties of loess.

Moisture Content (%)	Dry Density (g/cm ³)	Density (g/cm ³)	Specific Gravity	Void Ratio
16	1.503	1.858	2.711	0.768

A two-step process for preparation of the sample was used with each dry-wet cycle. The first step is sample saturation, which is briefly described as follows. The specimens were saturated by the vacuum saturation method. Filter papers and porous stones were firstly placed on the top and bottom of the soil sample. Then, the soil sample was fixed in a saturator chamber, as shown in Figure 3a, and then the saturator chamber with the soil sample was tightened with screw nuts and placed in a vacuum container (Figure 3b). After that, the soil specimen was submerged in de-aired water inside a vacuum container for at least 24 h to achieve a degree of saturation greater than 97% [36,37]. The drying phase was followed by wetting. After saturation, the soil sample was taken out by loosening the screw nuts and removing the filter papers and porous stones. Then, the soil sample sealed by the saturator chamber was placed in a drying oven at about 105 °C for 48 h to fully remove its water content [38,39]. Next, the soil sample was taken out and cooled down. This process, consisting of saturation and drying phases, is called one dry-wet cycle in this study. After the last dry-wet cycle, the corresponding water required to obtain the target water content was dripped on the top surface of the soil sample, and then the soil sample was wrapped with a plastic wrap and placed in a humidifier for 48 h to obtain a homogeneous sample in room temperature [40,41]. In this study, samples with different dry-wet cycles (0, 5, 10, 15, and 20) were prepared and the sample after 10 dry-wet cycles was shown in Figure 3c.

Figure 3. Specimen with the dry-wet cycles. (a) Frame saturator chamber, (b) vacuum container, (c) specimen after dry-wet cycles, (d) triaxial chamber.

2.2. Testing Apparatus

The FSR-20 triaxial creep apparatus for the testing cylinder of soil samples with a height of 125 mm and diameter of 61.8 mm in the State Key Laboratory of Continental Dynamics in China (see Figures 3c and 4) was utilized in this study. As shown in Figure 4, the apparatus consists of several parts, such as an axial loading system, pore water pressure controlling system, confining pressure controlling system, matric suction controlling system, data measurement, and a collect system. By using a pneumatic servo control system, the apparatus is capable of providing not only constant shear stress but also constant air pressure for a long time with high accuracy [3,42]. Creep tests can be carried out for confining pressure up to 1 MPa, pore water pressure up to 500 kPa, axial load up to 2 MPa, and pore gas pressure up to 500 kPa. The tests may be run either undrained or consolidated undrained with or without pore water pressure measurement, or drained condition. In this study, drained creep tests were conducted on loess samples.

Figure 4. FSR-20 triaxial creep apparatus.

2.3. Testing Scheme

According to the basic physical index properties listed in Table 1, samples with a moisture content of 16% were tested by using multi-level loading method [4,43]. Considering the density ($\rho = 1858 \text{ kg/m}^3$) and the thickness (20 m) of the overlying loess, the confining pressure of 200 kPa was chosen for the triaxial creep test. The multi-level loading method used in this study is described as follows: the first level of deviatoric stress was applied to the specimen until the stability was attained when the deformation of the specimen was less than 0.01 mm in 24 h. To find an optimum time during which the deformation of the specimen was less than 0.01 mm, a series of preliminary tests were conducted, where 24 h, 36 h, and 48 h were used for specimens with the same testing conditions. The creep shear test results show that for the cases of 24 h, 36 h, and 48 h, the strength and strain-time curves of loess have no obvious difference, indicating that 24 h is enough for obtaining the stability state of the loess. Therefore, 24 h was selected here from the point of view of time saving. Then, the second level of deviatoric stress was applied to the specimen until the stability state was achieved. The specimen was subjected to shearing until creep failure occurred at some level of deviatoric stress. In this study, the failure occurred in the specimen when the strain of specimen reached 20% following the previous study concluded by Xie et al. [44]. The samples after different dry-wet cycles were subjected to consolidation and shearing in the conventional triaxial compression test to calculate the instantaneous failure strength. Then, the loading scheme of the triaxial creep test (Table 2) was determined according to the instantaneous failure strength.

Table 2. Loading scheme of the triaxial creep test.

The Number of Dry-Wet Cycles	Deviatoric Stress/kPa
0	25, 50, 62.5, 75, 87.5, 100, 150, 250, 350
5	50, 100, 150, 200, 250, 300
10	50, 125, 200, 250, 300
15	50, 100, 175, 250
20	50, 100, 175, 250

3. Test Results

Based on the experimental data collected, the typical creep strain curves for loess with a different number of dry-wet cycles is plotted in Figures 5–9. After that, according to Boltzmann’s linear superposition principle [45,46], the creep curves corresponding to each level of deviatoric stress was obtained by using “the coordinate translation method” [47,48]. Figures 5–9 show the whole process curve of creep for loess and creep curves of loess with a different number of dry-wet cycles. In Figures 5–9, q represents the deviatoric stress, ε is strain, w is the moisture content, and t is time.

Figure 5. (a) The whole process curve of creep for loess without dry-wet cycles, (b) creep curves of the loess without dry-wet cycles.

Figure 6. (a) The whole process curve of creep for loess with 5 dry-wet cycles, (b) creep curves of loess with 5 dry-wet cycles.

Figure 7. (a) The whole process curve of creep for loess with 10 dry-wet cycles, (b) creep curves of loess with 10 dry-wet cycles.

Figure 8. (a) The whole process curve of creep for loess with 15 dry-wet cycles, (b) creep curves of loess with 15 dry-wet cycles.

Figure 9. (a) The whole process curve of creep for loess with 20 dry-wet cycles, (b) creep curves of loess with 20 dry-wet cycles.

It can be observed from Figures 5–9 that the characteristics of the whole process curve of creep for loess and creep curves are as follows: (i) The specimen with different dry-wet cycles underwent three typical creep stages, namely the decelerating creep stage, the steady state stage, and accelerate creep stage. With the same number of dry-wet cycles, the creep curve tends to be flat with an increase of time when a small load is applied, that is, the steady state stage. However, with a higher loading, the creep curve of the stable phase increases linearly with time. (ii) The slope of the curve corresponding to the steady state stage increases with an increase of loading. However, sudden failures could be observed within the loess specimen once the load exceeds a certain value. For example, when the deviator stress of the sample with 20 dry-wet cycles increased to 250 kPa, the deformation dramatically increases. (iii) With the increase of the number of dry-wet cycles, the maximum value of the deviatoric stress corresponding to the creep failure gradually decreases, indicating that the creep strength of the sample is deteriorated by the dry-wet cycles.

4. Discussion

4.1. The Long-Term Strength of Loess Samples with Different Dry-Wet Cycles

The long-term strength of rock and soil is an important parameter for assessing the stability of landslides [49,50]. At present, the main methods to obtain long-term strength through creep test curves include the isochronous curve method [3,51], which uses the creep test curve and the Boltzmann superposition principle [52] and states that the stress response of a system to a time dependent shearing deformation may be written as the sum of responses to a sequence of step strain perturbations in the past [53], to obtain the stress-strain isochronous curves corresponding to the different deviatoric stress at the same time [54]. Figure 10a–e show the isochronous curves corresponding to the creep curves of the samples after five kinds of dry-wet cycles ($n = 0, 5, 10, 15, 20$). Based on the isochronous curves, the long-term strength (q_L) was obtained.

The experimental data listed in Table 3 was plotted in Figure 11. One can observe that there is a clear correlation between the long-term strength and the number of dry-wet cycles. The overall relationship between the long-term strength of loess and the number of dry-wet cycles can be described by the following equation:

$$q_L = 123.50e^{(-n/9.98)} + 127.33, n \leq 20, \quad (1)$$

where q_L is the long-term strength measured in kPa and n is the number of the dry-wet cycles.

Figure 10. Cont.

Figure 10. Creep isochronous curve after different dry-wet cycles. (a) $n = 0$, (b) $n = 5$, (c) $n = 10$, (d) $n = 15$, (e) $n = 20$.

Table 3. Long-term strength after different dry-wet cycles (q_L).

n	0	5	10	15	20
q_L	250	206	172	150	148

Figure 11. The fitting curve of the long-term strength after different dry-wet cycles.

It is clear that the long-term strength of loess decreases when increasing the dry-wet cycles. However, the reducing magnitude of long-term strength gradually decreases with the increase of the number of dry-wet cycles, until it reaches a constant value. That is to say, the long-term strength of the loess and the number of dry-wet cycles ($n \leq 20$) shows an exponential decreasing relationship (see Equation (1)).

4.2. Creep Damage Mechanism of Loess Samples Due to the Dry-Wet Cycles

The creep damage mechanism of the loess samples due to the dry-wet cycles was explained from the perspective of macro pictures of the loess samples after creep failure and the change of long-term strength with dry-wet cycles. Figure 12 shows loess samples after experiencing creep failure. One can observe that the obvious failure surface did not appear in the specimen, whereas the bending and bulging occurred on the side of the specimen. Furthermore, as the number of dry-wet cycles increases, the phenomenon of bending and bulging of the specimen becomes more noticeable. Such a phenomenon can be explained as follows: under the effect of a dry-wet cycle, the microstructure of loess is destroyed due to the repeated migration and loss of soluble salts between soil particles in the loess sample [8,10]. Moreover, the dry-wet cycles also promote the development and expansion of joint fractures in the loess sample [7], resulting in the worsening of the creep mechanical properties (see Table 3 and Figure 11). As the number of dry-wet cycles further increased, the dissolved salts in the loess sample gradually dissolved in water, which results in the coarse particles being further dispersed and disintegrated and the total pore volume of the sample being increased [25]. Therefore, the creep curves of the loess specimen show a strain-softening pattern, and the bending or lateral swelling occurred in the specimen (see Figure 12, $n = 5$ and $n = 10$). When the number of dry-wet cycles reaches a certain value, structural stability (micro- and macro-structure stability) within the loess soils was achieved. Consequently, the long-term strength of loess samples tends to be stable (see Figure 10, $n = 15$ and $n = 20$), causing the creep mechanical properties to be consistent with each other.

Figure 12. Specimen after creep failure.

4.3. Limitations of the Experimental Test in This Study

Concerning the influence of dry-wet cycles, the experimental results herein can be used for the determination of numerical simulation parameters and for better evaluating the long-term stability of loess slopes. Therefore, the study would be beneficial to understanding the time-dependence of the mechanical behaviors of loess soils as well as the long-term stability of loess slopes, which provide the basis for understanding the mechanical behavior of the loess under the effect of dry-wet cycles, as well as guidelines for the prevention and

prediction of loess landslide stability. However, there are some potential limitations in this study that could be addressed in future research. First, the loess samples were sheared under a saturated condition with a maximum value of 20 dry-wet cycles, whereas the triaxial creep tests were not conducted on unsaturated loess samples with a wide range of dry-wet cycles. Therefore, the conclusions and theoretical formulas obtained in this study have certain restrictions. Secondly, the water used in this study is distilled water, which is unrealistic due to the fact that the water in the field contains many mixtures due to solute transport and other chemical effects [10,55–57]. Finally, the influence of dry-wet cycle on loess in the field is very complicated due to the influence of rainfall, irrigation water, evaporation, and other factors [8,9,11,12], which could not be simply simulated by dry-wet cycles. On the other side, it is difficult to estimate the actual number of dry-wet cycles that the loess experienced in the field. Thus, there are some difficulties in applying the experimental results in this study to engineering practice. All limitations above would be considered in future research.

5. Conclusions

To assist in the understanding of the time-dependent behaviors and the long-term stability of loess slopes after dry-wet cycles, the mechanical properties of intact loess samples were investigated through triaxial creep tests. The following conclusions can be drawn according to the obtained experimental results:

- (i) With the same number of dry-wet cycles, the strain-time curve of the loess samples shows a similar trend, where the strain eventually reaches a certain value with an increase of time when a small load is applied, whereas the creep curve of the stable phase increases linearly with time when the loess specimen is subjected to a higher loading. As the number of dry-wet cycles increases, the maximum value of the deviatoric stress corresponding to the creep failure gradually decreases, indicating that the deterioration of triaxial compressive strength is attributed to the dry-wet cycles.
- (ii) The long-term strength of loess samples with different dry-wet cycles was obtained by using the Isochronous Curve Method, and the long-term strength of loess samples and the number of dry-wet cycles showed an exponential decreasing relationship.
- (iii) The creep damage mechanism of loess samples due to dry-wet cycles can be explained as follows: the dry-wet cycle causes repeated migration and loss of soluble salts between soil particles in the loess sample, which results in damage of the sample's microstructure. Consequently, the development and expansion of joint fractures within the loess samples were also aggravated. The combined effects of microstructural damage and expansion of joint fractures causes a greater deterioration in the creep properties of loess soils.

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