Effects of Freeze-thaw and Dry-wet Cycles on the Collapsibility of the Ili Loess With Variable Initial Moisture Contents

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Abstract

Suffering from seasonal climate changes, the loess in the Ili region of Xinjiang is frequently subject to cycles of freezing-thawing (F-T) and wetting-drying (W-D), and the engineering properties of the loess are highly variable. In the present research, the collapsibility characteristics of the loess slope located in Xinyuan country is investigated, for which the uni-axial compression tests were carried out with the consideration of various F-T and W-D cycles. In parallel, both the SEM and NMR tests were carried out. Test results obtained from the research indicated that both F-T cycles and W-D cycles exacerbate the deterioration of the loess and the most serious situation will be reached after after 6–10 cycles. Under these two physical cycles, the micro-structure of the loess generally develops from relatively aggregated state to the dispersed one. Correspondingly, the porosity of the loess increases initially, followed by an obvious descending with wet-dry cycles. Whereas, the characteristics of the loess subjected to the F-T cycles is opposite. The in-behind reason is that the irreversible alteration of the loess micro-structure attributed to the frost heave force generated by F-T cycles and the water absorption-swelling effect are accounted for. The main contribution of this study is to give more explanations for the causes and action mechanisms of loess wet subsidence in seasonal permafrost zones, and provide a scientific basis for loess wet subsidence disaster prevention and control.

INTRODUCTION

Located in the western Tianshan Mountains of Xinjiang, the Ili River Valley is one of the typical seasonal permafrost area in China. The widely distributed loess in this region is of significant thickness and loose structure[1]. Attributed to its specific topographical, geographical, and climatic conditions, the Ili loess generally undergoes the prolonged wet-dry and freeze-thaw cycles[2]. Consequently, the loess usually suffered from the pronounced degradation in its mechanical properties[3, 4] and strong susceptibility to wet subsidence[5–7]. This is described as “three small (i.e., low dry density, low water content and low saturation), two large (i.e., thick collapsible soil layer, high porosity), and one zero (the absence of ancient soil layers)” [8]. As one of the most critical engineering properties, the collapsibility of loess is characterized by abrupt changes, discontinuity, and irreversibility. This property can cause severe problems such as landslides, roadbed subsidence, and dam leakage, posing significant risks to engineering projects[9–10].

Currently, numerous scholars have carried out corresponding researches on the collapsibility characteristics of loess under different cycle modes and initial water contents. Regarding the collapsibility of loess under F-T cycles, Wang et al. found that the secondary collapsibility coefficient of loess increases towards a specific value with the number of F-T cycles[11]. Song et al. discovered that F-T cycles have a dual effect of strengthening and weakening on loess with different dry densities, leading to corresponding changes in its mechanical properties[12]. Qi et al. conducted mechanism analysis on the variation of strength parameters of overconsolidated soil through F-T cycle tests, suggesting that the proportion of macropores decreases during the F-T process, leading to an increase in the number of contact points between soil particles and structural weakening caused by interparticle connections[13].
Gu investigated loess deformation and collapsibility during F-T cycles, finding that these processes disrupt soil particle connections, causing volume and porosity increases, thereby altering the wetting and subsidence characteristics[14]. Chamberlain E J studied the changes in permeability and structure of four fine-grained soils during F-T and found that F-T resulted in a decrease in the pore ratio and an increase in the vertical permeability attributable to a decrease in the volume of fine particles in the pore space[15]. Edwin et al. conducted laboratory F-T cycle tests on fine-grained soil, revealing that F-T cycles significantly change the structure[16]. Research on the collapsibility of loess under W-D cycles has yielded several insights. Malusis M. A. et al. observed that as the number of W-D cycles increases, the hydraulic conductivity of the soil also increases, alongside more pronounced vertical shrinkage[17]. Zhang et al. found that repeated W-D cycles reduce matrix suction in unsaturated soil, leading to irreversible changes in its mechanical properties[18]. Liu et al. noted a decline in shear strength of remodeled loess with more W-D cycles, while the permeability coefficient k notably rises[19]. Sillanpaa M. et al. found that W-D cycles enlarge the average diameter of macroparticles in loess without significantly altering the soil composition[20]. Mao et al. discovered that W-D cycles increase the porosity and decrease the dry density and cohesion of compacted loess, suggesting a weakening effect and potential for secondary wetting[21, 22]. Zhang et al. investigated the strength and deformation of loess under humidification and dehumidification, introducing "humidification deformation" to describe the deformation characteristics of wet-sagged loess with increased moisture[23].

Collapsibility is one of the critical engineering parameter to be accounted for[10]. There are lots of theories and assumption developed previously, including the capillary hypothesis [24], salt solubility hypothesis [25], colloid insufficiency theory [26, 27], water film wedging theory [28], under pressure theory [29, 30], and structural theory [27, 32, 34, 35]. Among them, the structural theory, which believed that the collapsibility of loess is controlled by its own structures rather than other parameters, has been well verified by subsequent investigations and widely adopted [36], the collapse and structural properties of natural loess are simulated mainly by artificially preparing loess [37]. Restricted by testing instrument, there is no systematical investigation carried out to explore the structural characteristics of loess[38, 39]. With the rapid development of modern equipment, in particular in terms of the invention about the SEM, the microstructure of the loess, including its anisotropy, inhomogeneity, and nonlinearity, have been well understood [40]. Subsequently, both the classification of microstructures and engineering properties of the loess were captured [31, 42], which have made contribution to the elucidate the in-behind collapsibility mechanism [43–47]. Other research, such as the development of microimage processing software and the establishment of the quantitative analysis were also conducted in parallel [48–50].

As discussed above, current research generally focuses on the macroscopic properties of loess subjected to various cyclic effects, most of which are related to the shear strength. However, only limited studies was carried out to explore the collapsibility mechanism and the single parametric analysis is not complete. Considering that a large amount of factors will affect the collapsibility of loess indeed, comprehensive research about the evolutionary laws and collapsibility mechanics of loess are thus requested. In the present research, the loess collected from Ili region of China was experimentally investigated to fill up aforementioned research gap. The collapsibility behavior of Ili loess subjected to F-
T and W-D cycles was investigated from the macroscopic perspective and then micro-structural features of degraded loess was also evaluated. Integrating these two analytical perspectives will elucidate the mechanisms of collapsibility in Ili loess, offering insights and theoretical guidance for engineering construction in similar regions.

**EXPERIMENTAL PROGRAMME**

**Raw materials and preparation of samples**

The loess used in the present research was taken from Xinyuan County in the Ili region (see Fig. 1). As suggested by GB/T50123−1999 [51], some critical parameters (e.g., the moisture content, liquid limit, specific gravity, and maximum dry density) of the loess were experimentally tested and the averaged values of which are listed in Table 1. Moreover, the particle size distribution curves of the loess is presented in Fig. 2, indicating the fine-grained loess is of poor gradation. As depicted in Fig. 3, the optimum water content of loess in the study area is about 19% and the maximum dry density is about 1.91 g/cm³.

Before starting the preparation of test samples, the lumped loess were air-dried in a cool place and then ground with a wooden mill. Afterwards, these prepared loess would be sieved by a 2 mm mesh. Samples were then sprayed to achieve the designed water contents (i.e., 6%, 10%, 14%, 18%, and 22%). Moreover, these samples would be moved to a sealed containers for 24 hours before the laboratory tests. Meanwhile, Remolded samples with a degree of compaction of 100% were also prepared.

<table>
<thead>
<tr>
<th>Density /(g·cm⁻³)</th>
<th>Dry Density/(g·cm⁻³)</th>
<th>water content /%</th>
<th>liquid limit /%</th>
<th>plastic limit/%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.36</td>
<td>1.86</td>
<td>17.60</td>
<td>28.10</td>
<td>19.10</td>
</tr>
</tbody>
</table>

**Freeze-Thaw Cycling(F-T) Test**

The constant temperature and humidity test chamber (No. JW-2000) was applied to simulate the impact of F-T action on the Ili loess. Referred to local meteorological data during past decade and other information reported by academic scholars [50], the freezing temperatures were given initially (e.g., -5.0°C, -10.0°C, -15.0°C, and −20°C) and the thawing temperatures (5.0°C, 10.0°C, 15.0°C, and 20°C) were also determined (see Fig. 4). It should be pointed out that the F-T cycles was alternated ranging from −20°C to 20°C and the frequencies of which were 0, 1, 3, 6, 10, and 20 times, respectively.

**Dry-Wet Cycling(W-D) Test**

The humidification process of the loess sample prepared for the W-D cycling test was conducted by the titration system. In practice, a titration tube was applied to achieve the initial moisture content, aiming at simulating the natural W-D cycles. Whereas, the electric blast drying oven was adopted for the
dehumidification process, for which the well humidicated samples were placed into the electric blast drying oven with a constant temperature of 50°C for 24 hours. In the present research, the initial moisture content of tested samples ranges from 6–22% with an increments of 4%. It should be note that the numbers of cycle frequencies are 0, 1, 3, 6, 10 and 20 times, respectively.

**Uniaxial Compression Test**

The high-pressure consolidometer produced by the Nanjing Soil Instrument Factory was adopted to conduct the uniaxial compression tests (see Fig. 5). Considering the effect of the loading rate on the law of compressive deformation behaviour as well as the real loading rate in actual engineering applications, the loading rate was set to 12.5kPa, 25kPa, 50kPa, 100kPa, 200kPa, 300kPa, 400kPa, and 600kPa, respectively.

As per GB50025-2004, the collapse coefficient ($\delta_s$) is defined as the additional subsidence of water saturated specimens with a unit-thickness after stabilizing under a given pressure. The collapse coefficient can be calculated via Eq. (1) and the classification of which is listed in Table 2 for reference:

$$\delta_s = \frac{h_p - h_{p'}}{h_0}$$

where, $h_p$ represents the height of the sample after compression and stabilization at a given pressure, mm; $h_{p'}$ is the height of the sample after extra settlement associated with water immersion (saturation) at a certain pressure, mm; $h_0$ is the original height of the sample before applying pressure, in mm.

<table>
<thead>
<tr>
<th>Types</th>
<th>Classification criteria ($\delta_s$)</th>
<th>Collapse degree</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non collapsible loess</td>
<td>$\delta_s &lt; 0.015$</td>
<td>None</td>
</tr>
<tr>
<td>Collapsible loess</td>
<td>$0.015 \leq \delta_s \leq 0.03$</td>
<td>Slight</td>
</tr>
<tr>
<td></td>
<td>$0.03 \leq \delta_s \leq 0.07$</td>
<td>Medium</td>
</tr>
<tr>
<td></td>
<td>$\delta_s &gt; 0.07$</td>
<td>Strong</td>
</tr>
</tbody>
</table>

**Scanning Electron Microscope Experiment**

The surface morphology of samples will be captured through imaging of secondary electron signals of the SEM testing instrument. Herein, in order to obtain samples of microscopic changes after different numbers of F-T cycles and W-D cycles, microscopic specimens with dimensions $\Phi 50\text{mm} \times 20\text{mm}$ were
prepared and examined by the environmental SEM (FEI Quanta 250 FEG). Although the magnifications of 50x, 200x, 400x, and 800x were all evaluated, only the 800x magnification SEM images were selected for in-depth analysis in following section, when either the image quality or the representative were accounted for together.

**Nuclear Magnetic Resonance Experiment**

Samples exposed to W-D and F-T cycles are placed on the nuclear magnetic resonance analyzer (MesoMR23-60H-I). The NMR test was first calibrated and the water content and signal quantity data of the calibrated samples were measured to obtain the fitted curve equation, as shown in Fig. 6. The porosity of each sample will be calculated based on the monitored NMR signal via the fitting curve equation established previously.

**COMPRESSION TEST RESULTS**

**Influence of F-T Cycles**

The repeated water-ice and ice-water phase changes are the normal phenomenon for the loess subjected to F-T cycles. The free water in the loess pores turns to ice associated with the movement of the inner particles and results in the volume expand. Whereas, the large-size pores developed in the freeze process will not revert to the small pores when the ice melt. In this case, the physical properties of the loess have been affected by the change of micro-structure. Figure 7 shows the variation process of loess collapsibility coefficient under different numbers of F-T cycles. As recommended by GB50025-2004, if the collapsibility coefficient of loess is under 0.015 at 200 kPa, the loess does not exhibit collapsibility characteristics. It is obvious from Fig. 7 that all tested samples are featured with the collapsibility without any freeze-thaw cycles, except for that with a water content of 22%.

However, the coefficient of these samples with a water content of 22% also increased to 0.027 under 200 kPa, reaching to a slight collapsibility level. Other samples exhibited a significant reduction in collapsibility coefficients after three cycles. Among them, the specimens with a large water content (10%, 14%, and 18%) does not exhibit the collapsibility. Whereas, the collapsibility of sample with a water content of 6% developed from moderate to slight level. Experimental data successfully reveal that the freeze-thaw cycles significantly affects the collapsibility coefficient of tested specimens, in particular when the water content is below the optimum level. In this situation, the collapsibility coefficient of specimens usually decreased with an increased freeze-thaw cycles, and finally to be stabilized. It also indicated that the most significant degradation occurred after three freeze-thaw cycles with a minimum value. Conversely, the collapsibility coefficient of these specimens with a water content above the natural level, gradually increases and then stabilizes until the final F-T cycles.

**Figure 7.** The collapsibility coefficient under different F-T cycles.

The possible reason for these difference in terms of the collapsibility characteristics is attributed to the disruption and reorganization of the soil microstructure caused by F-T cycles[15, 36, 53–55]. With
repeated F-T actions, the formation and expansion of pores may increase the number and total area of pores, enhancing the soil's water storage capacity, thus resulting in greater swelling.

**Influence of W-D Cycles**

Figure 8 shows the variation process of loess collapsibility coefficient under different W-D cycles. It is obvious that there is an initial increase, flowed by a decrease, and the gradually achieve stable as the number of W-D cycles increases. Without undergoing the W-D cycles, all samples expect for the one with a water content of 22% exhibit an obvious collapsibility characteristics. However, the collapsibility coefficient of the sample with a water content of 22% under a standard pressure of 200 kPa also increased to 0.023 after 10 W-D cycles. For the other four groups of loess samples, the collapsibility coefficient reached its maximum value after 6 cycles. That is, the number of W-D cycles had a significant impact on the collapsibility behaviour of loess samples with different water contents. In detail, if the water content of the sample exceeded the natural water content, the collapsibility coefficient of the sample with a water content of 22% only peaked after 10 cycles, suggesting a delayed response in terms of collapsibility.

**Figure 8.** The collapsibility coefficient under different W-D cycles.

**Influence of Initial Water Content**

It has been well noted that the loess collapsibility initiates together with the immersion rather than the reach of saturation, which indicates the importance of moisture content when the collapsibility is accounted for. Figures 9 and 10 depict the variations in the collapsibility coefficient of tested samples with different initial water contents under varying F-T and W-D cycles, respectively.

**Figure 9.** The collapsibility coefficient of the loess with different water-content under F-T cycles.

It can be observed from Figs. 9 and 10 that the collapsibility coefficient of the loess sample generally decreases as the initial water content increases under F-T cycles and W-D cycles. It is obvious that the curves shown in Figs. 9 and 10 are smooth and only slight irregular fluctuations were observed for these samples with water contents of 18% and 22% after 10 W-D cycles. This is an important evidence to support that the effect of initial water content is much more significant than that of cycling actions. If the initial water content is within the range of the optimal water content, a higher initial water content will lead to a small collapsibility coefficient. This effect is attributed to the dissolution of soluble salts and the absorption of water by some clay minerals. With the reduced cohesion and structural integrity, the collapsibility coefficient of the loess also exhibits a descending trend.

The values of the collapsibility coefficient also varies with vertical load and there is an initial increase, flowed by the subsequent decrease. For most samples, the values of the collapsibility coefficient increases with the vertical load, for which is generally below 300 kPa. Once the load exceeds 300 kPa, the values of the collapsibility coefficient decreases with the vertical load. Because that the lateral
deformation of the sample is somehow confined, the increase of the collapsibility coefficient with vertical load is not always obvious.

The collapsibility coefficient of loess initially increases and then decreases with an increase in pressure under F-T cycles, for which there is a peak point at a given pressure of 400 kPa. It is much different from the observation obtained from the W-D tests. When the water content of samples are larger than 14%, the loess are non-wetted or slightly wetted without cyclic action. If the water content is less than 14%, the collapsibility of loess developed from the slight level to the medium one. This indicates that drier loess are more collapsible and pressure-sensitive. It indicates that low water content soil samples are more collapsible and sensitive to pressure, which is due to the fact that loess with higher water content is better saturated before immersion and the deformation and collapsibility coefficients are reduced after wetting.

**Figure 10.** The collapsibility coefficient of the loess with different water-content under W-D cycles.

**SCANNING ELECTRON MICROSCOPY (SEM) TEST RESULTS**

In this section, the sample with a water content of 18%, being nearest to the optimal water content, were selected from five typical groups for SEM analysis. The qualitative analysis will focus on the microstructure examination of loess, covering the analysis on the morphology of skeletal particles, structural particle characteristics, contact relationships, association modes, pore types, and the degree of cementation [32, 56–58].

**Qualitative Analysis of Microstructure under Freeze-Thaw Cycles**

The qualitative analysis on SEM images of loess samples under F-T cycles (see Fig. 11) was conducted. For these samples without any F-T cycles, the loess particles predominantly featured with a powdery, ellipsoidal, globular, elongated, columnar, and irregular morphology, with a gravelly and mosaic appearance. The primary contacts in between were mosaic, associated with face-to-face cementation and inter-granular mosaic pores attributed to soil remodeling. The main contact between particles changed to scaffold contacts after 6 freeze-thaw cycles and the primary pore type becomes to be intergranular voids. The predominant microstructure types were granular, scaffold, point contact with micro-cementation structure. By the tenth cycle, a semi-coagulated structure was emerged, and granular, scaffolding, and point contact-semi-colloid features were developed during this period. Following 20 freeze-thaw cycles, the particle structure are featured with basal and adherent types. As can be seen from Fig. 11, there are many point contacts and intergranular voids. Meanwhile, the microstructure of the loess transformed into granular, dispersed, point contact with partial cementation.

**Figure 11.** SEM images of representative samples under different F-T cycles.

Based on above discussions, it can be summarized that the microstructure of loess evolved from a granular, mosaic, surface-cemented microcementation structure to a clustered, dispersed, point contact-
cohesive structure. Attributed to reduced cohesion of the loess sample, the inner particles exhibited a dispersed trend with the increased pore space. Once the water retention was enhanced, the values of collapsibility coefficient will be enhanced.

**Qualitative Analysis of Microstructure under Dry-Wet Cycles**

The SEM images of loess samples under W-D cycles are shown in Fig. 12. The qualitative analysis of these images shows that the microstructure of the loess transitioned from a granular, mosaic, and surface-cemented microcementation to a shelf, dispersed, and point-contact-cohesion structure, as the number of W-D cycles increased. Compared to reference samples not subjected to dry-wet cycles (N = 0), the particles within the sample progressively fragmented through the cycles. Because that large particles broke down into smaller particles forming aggregates during the W-D cycles, leading to the filling of large pores with these particle aggregates. Consequently, the large pores decreased gradually, while the small pores decreased slightly during the aggregation of particles. Finally, medium pores increased due to the breaking down of large particles and the agglomeration of small particles. This pattern suggests that the soil particles experience more degrading and disintegration than cohesion during dry-wet cycles, resulting in an increase in large and medium pores. Combined with the dissolution of salt and dispersion of clay particles, reduction in cohesion weakens the soil structure, and facilitating the collapsibility.

**Figure 12.** SEM images of representative samples under different W-D cycles.

**NUCLEAR MAGNETIC RESONANCE TEST RESULTS**

**Effects of F-T Cycles on Pore Size Variation**

Figure 13 shows the porosity changes in loess samples under different cycling modes. Porosity of loess specimens subjected to F-T cycles showed a tendency to increase first, then decrease and finally increase. The pore size reaches its peak at the 6th cycle, showing a similar pattern to the variation of the collapsibility coefficient of loess under F-T conditions as discussed in Section 2.1. In the early stages of F-T cycling, the change in porosity is subtle until a noticeable increase occurs by the third cycle. This suggests that structural damage to the soil begins to intensify at this point, attributed to the expansion and subsequent disruption of loess particle connections due to freezing. Upon thawing, the large pores formed by freezing and expansion between particles decrease as the particles settle under gravity, resulting in a reduction of original large pores and an increase in small pores. After the 6th cycle, the pore size of the soil starts to diminish and then stabilizes, indicating a gradual stabilization of the disruptive effects of the F-T cycles.

**Effects of W-D Cycles on Pore Size Variation**

From Fig. 13 Changes in porosity of loess specimens in different cycling modes. The porosity of samples after W-D cycles increased initially, then decreased, peaking at the tenth dry and wet cycle. This pattern aligns with the collapsibility coefficient changes in loess under W-D cycles discussed in Section 3.2. Compared to the sample not subjected to W-D cycling (N = 0), the porosity of the samples exposed to
such cycling increased notably, with significant changes occurring during the initial cycles (N = 1 and N = 3). As the number of W-D cycles increased, the rate of porosity change diminished. This trend is attributed to the compaction of the soil body during the initial cycles, where internal moisture movement causes small particle migration and the creation of water transport channels. This effect is more pronounced in the early stages of cycling, leading to larger changes in porosity. However, as the cycles progress, established water transport channels reduce the impact of moisture movement on soil particles, stabilizing the internal particle structure and gradually leading to a decrease in porosity changes until they stabilize.

**THEORETICAL DISCUSSIONS**

**Collapsibility Mechanism of Loess under F-T Cycles**

The collapsibility coefficient of loess experienced the initial F-T cycles is generally reduces somehow, which mainly attributed to the disruption of original cementation between small particles together with the reduction of the cohesive force in between [57]. On the other hand, the frost heaving and migration forces generated during the F-T process also weaken the adhesive forces between different particles, promoting the migration of moisture within the loess. These effects combine to decrease water adsorption of the loess and thus reduces the collapsibility coefficient before subsequent F-T cycles.

However, the repetitive F-T action induces continuous movement of free water within the soil and diminishes particle occlusion as the number of cycles increases. This irreversible process results in a reduction in the cohesive force (see Fig. 14). Meanwhile, the porosity of loess exhibited an initial increases, then decreases, and eventually rises again with more F-T cycles. contributed to the breakage of large particles and accumulation of small particles, the number of medium-sized pores increased while the number of large and small pores correspondingly reduced. As the increase of cycles, however, particles tends to be more rounded, the contact points between particles reduced and the loess developed from a compacted mode to a looser state. As a result, the enhanced water storage capacity bring side-effect on the collapsibility coefficient.

**Collapsibility Mechanism of Loess under W-D Cycles**

When the loess undergoes repeated W-D cycles, the internal particles experiences many times of absorbing and releasing together with structural expansion and contraction. The cyclic state leads to the lost of hydrophilic minerals between soil particles from their original state. This gradual reduction of the cementitious material within the soil will significantly weaken the bond strength and consequently decreasing the internal cohesion of the loess (see Fig. 15). As revealed by NMR test results, the loess porosity initially increases and then decreases with more W-D cycles, as the continuous wet-dry effect breaks down large particles and aggregates small particles. These combined factors make the loess structure transition from compact to loose, enlarging the pore space and enhancing conditions for wetting. As a result, the collapsibility coefficient of the loess increases after the W-D cycles, indicating progressively more severe collapsibility.
Collapsibility Mechanism of Loess under combined cycles

As per aforementioned discussions, it can be seen that the collapsibility characteristics of Ili loess is fundamentally due to irreversible changes of its microstructure [60], although the response mechanics of which are different. Under freeze-thaw cycles, the frost heaving and migration forces weaken the adhesive forces between particles, promoting the migration of moisture within the loess. Conversely, the repeated wetting and drying processes cause the particles continuously expand and contract. This leads to the detachment of hydrophilic minerals, a reduction in cementation, and weakened adhesion. Despite these differences existed, both cycling processes share a common effect. That is, the expansion and disintegration of aggregate units exceed compression and polymerization, resulting in increased porosity and soil volume expansion. Furthermore, both cycles transform the soil microstructure from aggregated to disaggregated, reducing particle cohesion and enabling conditions for particle slippage during collapsibility.

CONCLUSIONS

This study focuses on the loess collected from a natural loess slope in Yili Region, and investigates the changes in the collapsibility characteristics of remolded loess with different water contents under F-T and W-D cycles through indoor uniaxial compression tests (double-line method). The study also examines the variation mechanisms of loess microstructure using SEM and NMR tests. The following conclusions are drawn:

1) When the water content is less than the optimum water content, the collapsibility coefficient of the loess decreases initially, then increases, decreases again, and eventually stabilizes with an increase in the number of F-T cycles. However, when the water content of the soil sample is greater than the natural water content, the collapsibility coefficient of the soil sample gradually increases with an increasing number of F-T cycles, eventually stabilizing.

2) When the water content of the loess is less than the optimal water content, the maximum values of the collapsibility coefficients of the loess appear after six W-D cycles for the W-D cycle condition. Whereas, the collapsibility coefficient of the 22% water content soil sample only reaches its peak after 10 W-D cycles, if the water content of the soil sample is greater than the natural water content. It indicates that the effects of W-D cycles are more lagging on higher water content soil samples.

3) The microstructure of loess gradually transforms from granular, inlaid, surface cementation micro cementation structure to agglomerated, dispersed, point contact cementation structure under different cyclic conditions. Meanwhile, the porosity of soil samples experiences the initial increase and then decreases with dry wet cycles, and finally increasing with F-T cycles.
(4) The fundamental reason for the changes in the swelling characteristics of loess is that both types of cycling actions result in irreversible alterations to the soil's microstructure. The repeated cycling actions cause soil particles to undergo expansion and breakdown, weaken the cementation process, reduce the number of small pores between soil particles while increasing the number of medium-sized pores, leading to an increase in porosity, enhanced water retention capacity of the soil, and creating favorable conditions for loess swelling.

(5) The study reveals the mechanism of changes in the swelling characteristics of loess in the Ili region under different cycling actions. The frost heaving and migration forces generated by freeze-thaw cycles weaken the adhesive forces between soil particles, promoting the migration of moisture within the soil. Under dry-wet cycles, the soil particles undergo expansion and contraction due to water absorption and loss, leading to the detachment of hydrophilic minerals between soil particles, reduction of cementitious material, weakening of bond strength, and ultimately creating conditions for loess collapsibility.

Declarations

Data availability statement

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

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Author contributions statement


Additional information

The authors declare no conflict of interest.

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Figures
Fig. 1. Sampling Location.

**Figure 1**

See image above for figure legend.
**Figure 2.** The particle size distribution curve.

See image above for figure legend.
The optimum moisture content: 17.60%
The maximum dry density: 1.86g·cm$^{-3}$

Fig.3. The compaction curve.

Figure 3

See image above for figure legend
Figure 4

See image above for figure legend

Figure 5

Experimental flowchart.
Fig. 6. Calibration of water content.

Figure 6

See image above for figure legend
Figure 7

See image above for figure legend.
Figure 8

See image above for figure legend.
Fig. 9. The collapsibility coefficient of the loess with different water-content under F-T cycles.

Figure 9

See image above for figure legend
Figure 10

See image above for figure legend

**Figure 10**

The collapsibility coefficient of the loess with different water-content under W-D cycles.
Figure 11

See image above for figure legend
Figure 12

See image above for figure legend
**Fig. 13** Variation of pore size of soil samples under different cycling modes.

See image above for figure legend.
Fig 14. Microevolution of the loess under F-T cycles.

Figure 14

See image above for figure legend
**Figure 15**

See image above for figure legend.

**Fig 15.** Microevolution of the loess under W-D cycles.