Study on The Influence of Freezing and Thawing Cycle and Dry and Wet Alternation on Mechanical Properties and Engineering Application of Loess Slope

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Abstract

This article selects typical high-slope loess along the Baolan high-speed railway as the research object. Firstly, laboratory testing methods are used to conduct direct shear and consolidation tests on loess under freeze-thaw cycles, dry-wet alternation, and their combined effects to study the changes in its mechanical properties. The experiment found that rainfall infiltration is different due to different slopes. The negative pore water pressure at the top of the slope rapidly increased from −176.52 kPa to −139.094 kPa, and the volumetric water content also rapidly increased from 14.11% to 16.63%. The negative pore water pressure at the foot of the slope increased to −76.33 kPa, and the volumetric water content was 22.11%. At a given

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dry density, as the moisture content increases, regardless of the type of specimen, its cohesion, internal friction angle, and compression modulus gradually decrease while the porosity increment and compression coefficient increase. At a given moisture content, as dry density increases, regardless of the type of specimen, its cohesion, internal friction angle, and compression modulus gradually increase while the increment of porosity and compression coefficient gradually decrease. However, the internal friction angle, porosity increment, and compression modulus response to freeze-thaw action are closely related to initial dry density. At a given dry density and moisture content, as the number of cycles increases, the cohesion and compression modulus of the sample gradually decrease while the increment of porosity and compression coefficient increase.

Keywords: Freeze-thaw cycle, dry and wet alternately, freeze-thaw dry and wet cycle, slope stability.

1 Introduction

Loess slopes are widely distributed in China, and due to their unique physical and mechanical properties, they are easily affected by natural factors such as the freeze-thaw cycle and dry-wet alternation. Unsaturated soil is composed of solid, liquid, and gas, covering China's arid and semi-arid areas. As a typical representative of unsaturated soil, loess is a kind of olian sedimentary silt. Compared with other silt soil, loess has large pores. It has the characteristics of vertical joint development and water sensitivity all over the northwest, north China, and other plain and mountainous areas [1, 2]. In the inland with seasonal cycle changes, on the one hand, various engineering practices carried out in the loess seasonal frozen area, such as railway construction, foundation pit excavation, and various slope treatments, will subject the soil to the influence of new freezing and thawing. On the other hand, due to the interaction between water infiltration and evaporation of the flow from the ground, the soil water and gas exchange and then cause dry and wet damage.

"Belt and Road" policy, the construction of some major infrastructure has also entered a climax, such as the [3] of high-speed rail, highway, subway, and rail transit in northwest China. In the construction and operation process of these projects, the treatment problems of loess subgrade, slope, and tunnel will inevitably be encountered. The water inside the soil will be distributed, the size and spacing of the particles will change, the connection force between the soil particles will be destroyed, and finally, the mechanical properties of the soil will be changed.

As a robust weathering effect, they were freezing and thawing, the temperature effect affecting soil properties with the alternating seasons or the temperature difference between day and night. When the temperature increases, the soil moisture flows to the interior and the surface and sinks. This phenomenon is called the melting [4, 5] of soil. Due to the change of seasons, the temperature cycle fluctuates, and the soil experience in the seasonal frozen soil area produces repeatedly freezing and melting. The water field and temperature field inside the soil change accordingly, resulting in the physical and mechanical properties of the soil, such as dry density, cohesion, internal friction Angle, water content, pore ratio, permeability, strength, and other effects [6]. Therefore, the repeated frost and thawing of soil in seasonal frozen soil areas is of practical significance for studying soil engineering properties and preventing and controlling freezing damage in engineering entities.

Under the influence of rainfall and evaporation, the strength and deformation of the soil will produce irreversible damage. On the one hand, from June to September is the main rainfall season in northwest China, and the properties of the soil changes significantly, the soil connection weakens significantly, the structure destroys rapidly, and the soil sinks; in the spring and summer seasons, the soil evaporates under the combined action of dry climate and weathering force, and under the action of capillary, the moisture in the soil gradually accumulates at the contact point of coarse particles, and combines with some water-soluble salts, making the loess has a high strength [7, 8]. Northwest China is not only the main loess distribution area in China, but also affected by seasonal climate change. Under influence of freeze and thaw cycle, alternating dry and wet and even the combined action of both, the internal water redistribution, the microstructure of the soil, the size and spacing of the particles change, which destroy the connection force between the soil particles, cause the attenuation of soil strength, and finally lead to change of the mechanical properties of the soil. China is in the stage of vigorous development of infrastructure construction, and the properties of engineering mechanics of loess and the mechanics of unsaturated soil have a practical significance for the guidance of engineering construction [9, 10]. It is a long way to go to accurately evaluate the evolution of engineering mechanical properties of loess under complex climate conditions, and to prevent and treat the subsidence, cracking and landslide of loess foundation.

2 Numerical Model of Rainfall and Evaporation in Unsaturated Soil

2.1 Saturated-unsaturated Percolation Theory

Through the mass conservation equation, the saturation-unsaturated seepage control differential equation is formula (1):

$$\frac{\partial}{\partial x_i}\left[k_{ij}k_r(h)\frac{\partial h}{\partial x_j}+k_{i3}k_r(h)\right]+S=(C+\beta S_S)\frac{\partial h}{\partial t} \tag{1}$$

In the formula, k_{ij} is the saturated permeability tensor; k_{i3} is the saturated permeability coefficient when $j = 3$ in k_{ij}; $k_r(h)$ is the relative permeability coefficient; h is the head pressure; C is the water capacity, which is 0 in the saturation zone; β is the volume compression coefficient of water, in the saturation zone $\beta = 1$. In the unsaturated zone $\beta = 0$ Is the water storage rate; S_S is the source term; t is a time variable; x_i and x_j represent the horizontal and vertical directions, respectively.

2.2 Determination of Boundary Conditions for Rainfall and Evaporation

Rainfall seepage is related to the permeability coefficient of the soil, which is mainly divided into three situations:

When the rainfall intensity exceeds the saturation permeability coefficient, all the rainwater seeps into the soil. At this time, the boundary condition is the flow boundary, and the calculation formula is shown in Equation (2):

$$v(x,y,t)|r_2gn = q(x,y,t) \tag{2}$$

In the formula, v is the flow velocity; n is the direction of the boundary normal; v_{r_2} is the known flow boundary; $q(x, y, t)$ is a known function.

When the rainfall intensity is greater than the saturation permeability coefficient, some rainwater infiltrates and the rest is lost in the form of runoff. At this time, the boundary condition is the head boundary, and its calculation formula is shown in Equation (3):

$$h(x,y,t)|r_1 = h_1(x,y,t) \tag{3}$$

In the formula, h is the pressure head; r_1 is the boundary of the seepage zone; h_1 is a known function of spatial coordinates x, y, and t.

The initial evaporation intensity remains basically unchanged, but as surface water is lost, the evaporation intensity will continue to weaken. Therefore, the evaporation boundary condition is expressed as Equation (4):

$$v|r_2 = f_\theta(\theta) \tag{4}$$

Under influence of long-term dry climate, the surface maintains a low air-dry water content, and the evaporation force is almost unchanged, so the evaporation condition is. The calculation formula is shown in Equation (5):

$$h|r_1 = h_0 \tag{5}$$

In the Equation (5), h_0 is a constant function.

3 Experimental Design of Influence of Freeze-thaw Cycle and Dry-wet Alternation on Loess Slope

3.1 Nature and Preparation of The Test Specimens

The loess used in test is all taken from typical high slope of Baolan passenger dedicated line, which belongs to the south bank ladder of the Yellow River, the landform unit belongs to the loess beam, and the groundwater belongs to the diving type [11]. The geological soil layer is silt and silty clay, which belongs to the windy Q3 loess and is medium collapsible loess. The samples are manually sampled by professional workers at the slope side wall, and the earth extraction cylinder is sealed on site.

Figure 1 presents the preparation principle of test samples. All test samples strictly follow the preparation method [12, 13]. For test sample preparation, the soil in the cylinder with an aperture of 0.5 mm sieve, according to formula (6), calculate more groups of specific moisture content of sample water, through the surface of the water can evenly spray water distribution more uniform, need to artificially mix, stir good soil samples into the moisturizing tank, for use. Take out the soil samples, calculate the quality of the required various dry density samples according to formulas (7) and (8), and then the test sample [14] is prepared by the layered sample pressing method.

$$m_w = \frac{0.01 \times (w - w_0)}{1 + 0.01 w_0} \times m_0 \tag{6}$$

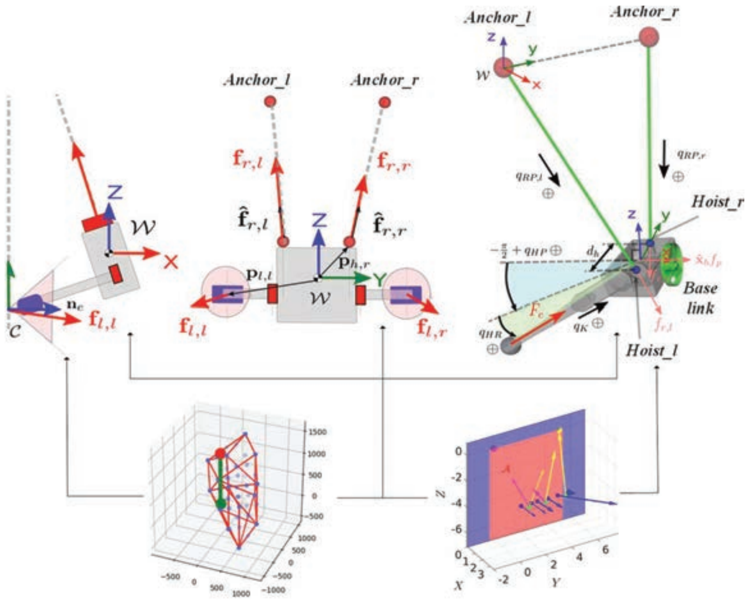

Figure 1 Example preparation principle.

$$\rho = \rho_d(1 + w) \tag{7}$$

$$\rho = \frac{m}{v} \tag{8}$$

3.2 Selection and Principle of The Experimental Equipment

3.2.1 Direct shear instrument

Due to large variation of dry density and moisture content, in thawing and dry and wet cycle sample is easy to produce cracks, the sample of the size of the size of the sample, in order to make the test is unified and more accurate results, this paper selects the sample freezing and thawing, dry and wet and before and after change of shear strength parameters [15, 16]. The test instrument adopts the electric four-straight shear instrument of the school geotechnical laboratory. Its structure is relatively simple, easy to operate, and has a stable performance of.

3.2.2 Fixator

Consolidation test According to the needs of the project, the rapid consolidation test, normal slow consolidation test, consolidation coefficient and

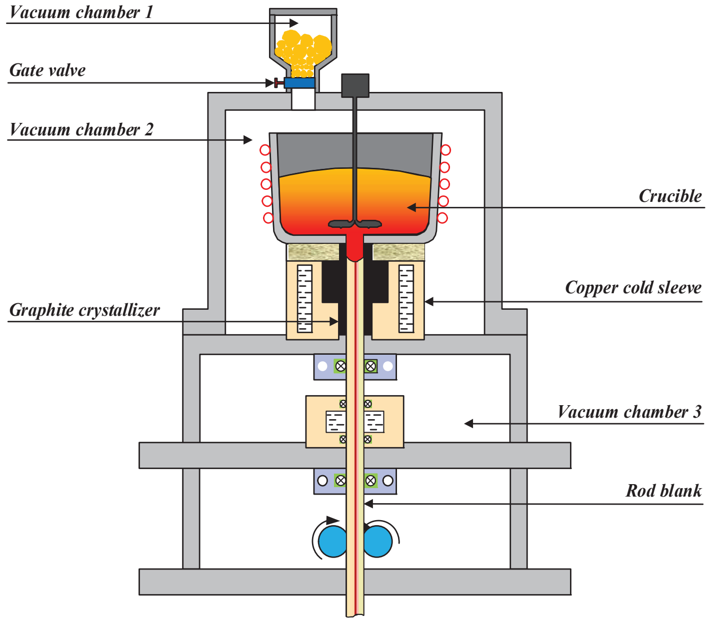

Figure 2 Design based on freeze-thaw cycle and dry and wet alternation.

early consolidation pressure can be determined for [17, 18]. Rapid consolidation test method can be used for samples that do not require consolidation coefficient, low settlement accuracy requirements or large permeability coefficient.

This paper does not involve the determination of the consolidation coefficient, so the rapid consolidation test method is used to study the influence of the freezing and thaw cycle, dry and wet alternation, and interaction between the two on the compression characteristics of soil consolidation [19, 20]. The test instrument required for this test is a single lever triple medium pressure instrument, as shown in Figure 2. First, put the prepared sample on the filter paper close to the moisture content of the sample; carefully put it into the tank (due to the consolidation compression test of unsaturated soil, there is no water in the tank); put a permeable stone, sample, permeable stone, pressurized cover, Then install the percentage meter, Adjust so that the end is on the same vertical line as the center of the pressure cover and the meter, And make complete contact with the parts, With a consolidation pressure of 25 kPa, 50 kPa, 100 kPa, 200 kPa and 400 kPa, If the sample displacement is not more significant than 0.005 mm Until the test is completed. It should be noted that since this consolidation test is unsaturated soil, attention should be paid to moisturizing the sample in the test. In this paper, the sample covers the towel with similar humidity to ensure test standardization [21, 22].

4 Experimental Results and the Analysis

Samples taken from Xi 'an Shaanxi, China, are typical Q4 loess with uniform soil, large pores, and relatively loose texture, which has typical characteristics of loess. During the sampling process, we follow the principle of reducing disturbance to ensure that the original structure of the sample is not destroyed. Laboratory soil mechanics tests are one of the essential means of research work, as well as preliminary work of geotechnical practice. The purpose of an indoor test is to understand the properties of the sample; in addition to the density, water content, porosity, water absorption, permeability, and other physical properties test, it should focus on the sample strength and deformation characteristics of the test [23, 24]. Only with the necessary indoor and field tests of the test sample, obtaining the relevant data, and clearly understanding the project can the economic and feasible design and construction work be done.

4.1 Description of Experimental Phenomena

After the freezing and thawing cycle, there is slight peeling and surface on the surface, which is due to the moisture migration during freezing; the surface moisture increases and forms ice crystals, and the frost swelling force is developed, the connection between soil particles is destroyed, fine particles increase; in the sample melting stage, the moisture spreads around and surface soil, resulting in the surface moisture content, and with the dissipation of the sample, the particles sink under the action of gravity, soil particles size and spacing change, the sample surface becomes loose, easy to fall off, therefore the test surface will appear [25] peeling and hemp surface.

The sample surface is rough and shows uneven cracks at the edge. This is because, during humidification and wetting, the specimen repeatedly expands and shrinks. With the addition and unloading of the substrate suction, the sample fatigue is destroyed, the cracks are developed, and even though the sample is broken and loose, the stress concentration occurs in the weak place between the soil particles, resulting in small cracks [26, 27]. Compared with freeze-thaw and dry and wet samples, the surface of the freeze-thaw and dry and wet samples is more seriously damaged, producing large pores, and the

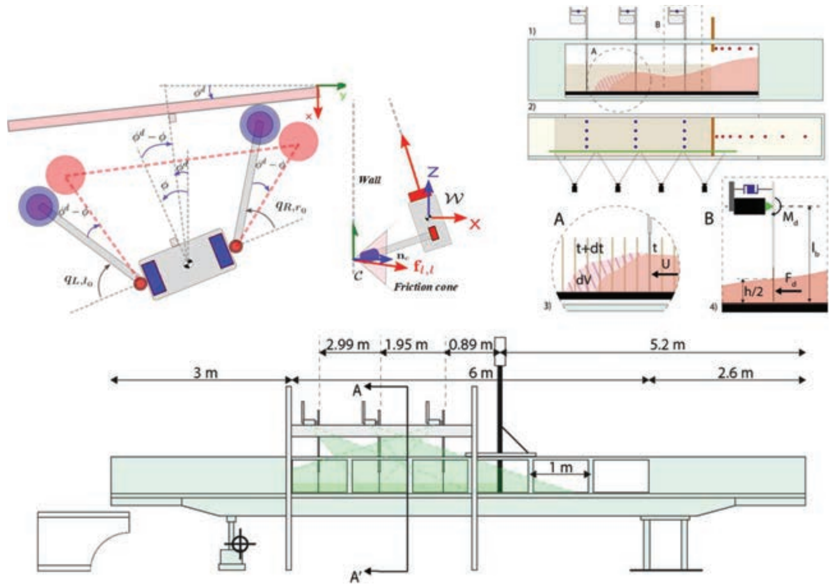

Figure 3 Mechanical properties and engineering application process of loess slope.

crack extension is more prominent and even becomes loose at the junction of the soil and the edge of the ring blade.

4.2 Analysis of The Results of Direct-shear Experiments

Figure 3 for the loess slope mechanical properties and engineering application process, the foundation of the bearing capacity, stability of the slope and the retaining structure is closely related to shear strength of soil, so shear strength parameters is particularly important [28].

4.2.1 Change of shear intensity parameters at different water content

The dry density is 1.62 g/cm^3, resulting from a shear test of samples at different water content. Analysis shows that shear strength and moisture content are negatively correlated (unfrozen, laundry, wet samples, dry and wet samples, and dry and wet samples). When the moisture content increased from 9% in the sample to 30%. Under a vertical pressure of 400 kPa, the shear strength of the sample exhibited a consistent downward trend, decreasing from an initial value of 288.108 kPa to 208.38 kPa and from 264.552 kPa to 197.508 kPa. Similarly, the shear strength of the dry-wet sample decreased from

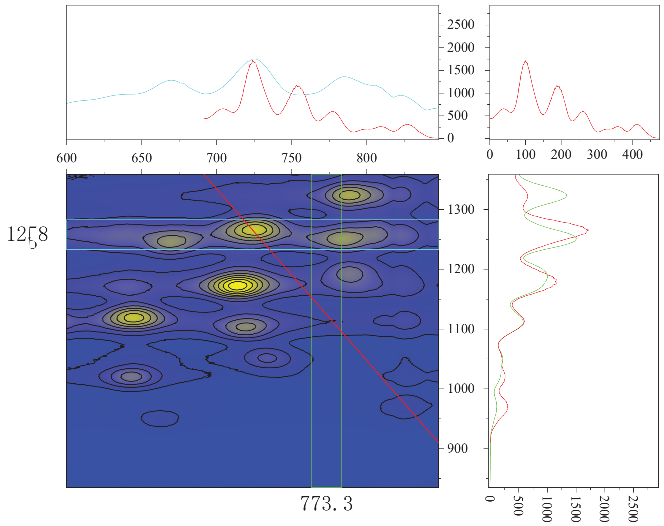

Figure 4 Variation of shear intensity parameters at different water content.

248.244 kPa to 155.832 kPa, and the freeze-thaw sample's shear strength declined from 239.184 kPa to 135.9 kPa. This consistent pattern persisted across upper loads of 100 kPa, 200 kPa, and 300 kPa, indicating a robust relationship between pressure and shear strength degradation. In addition, under the action of one freeze and thaw cycle, one alternating dry and wet action, and freeze and thaw wet, respectively, the strength of the sample was attenuated compared with non-freeze and thaw samples, and the attenuation of dry and wet and freeze and thaw samples was more serious, and the freeze-thaw samples were second.

The stress distribution, deformation characteristics, and failure modes of loess slope under different water content are studied through theoretical analysis and numerical simulation. The results show that with the increase in water content, the stress concentration of the loess slope is intensified, the deformation is increased, and sliding failure is more accessible. Figure 4 shows the change of shear strength parameters under different water content. With the increase of water content, the strength parameters of soil decrease, in which the cohesion decreases significantly, and the shear strength loss of loess combined by the freezing-thaw cycle, alternating dry and wet cycle, and freeze-thaw dry and wet cycle increases successively. The strength of unfreezing and wet samples is less than that of freezing and dry and wet samples. The internal friction angle shows the same pattern as the cohesive

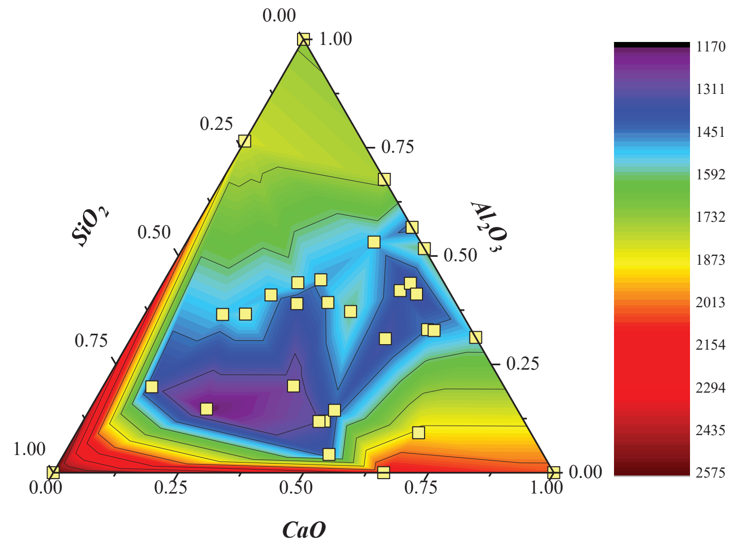

Figure 5 Soil quality analysis after dry and wet circulation.

force. The mechanism is mainly based on the following reasons: when the sample has a low moisture content, the water in the soil is frozen in situ, the water migration is not significant, and the large ice crystal cannot be formed. Therefore, the internal integrity damage of the freezing and thawing sample is limited, and the cohesion and internal friction Angle will not produce significant changes. However, when the water content increases, the water film between the particles thickens, and the volume of ice crystals between the soil particles increases after freezing. However, the soil cannot return to its previous state when melting. Thus, the cohesion force is reduced. In addition, when the sample has a high moisture content because the water film in the soil is thicker, the lubrication of the particles plays a leading role. Then, the sample's cohesion and internal friction Angle will be reduced to the minimum.

Figure 5 shows the soil analysis after the dry and wet cycle. On the other hand, when the moisture absorption increases and repeatedly, the soil damage occurs in the weak area of stress concentration, the specimen becomes broken and loose, and the moisture content increases, the moisture increases for lubrication between the particles, thus the sample adhesion and internal friction Angle are gradually decreased.

When the sample is under the influence of thawing and wet, frost and moisture migration make soil internal particle size and spacing change, coupling force weakening, and in the sample, repeated moisture expansion, wet dry shrinkage, soil uneven deformation, crack expansion, and matrix suction and unloading and promote the weakening of the strength of the soil, especially in the stress concentration, sample damage is more serious, cohesion sharply weakened, sample integrity severe damage, both accelerated the attenuation of the soil strength [29, 30].

For a sample with a given dry density, the cohesion and internal friction angle basically decrease linearly as the water content increases. A high correlation coefficient can be obtained by fitting the following function, which can be verified by the fitting function.

The formula of cohesion is shown in Equation (9), and the formula of internal friction angle is shown in Equation (10).

$$c = aw + b \tag{9}$$

$$\varphi = ew + f \tag{10}$$

Where c is the cohesion; w is water content; φ is internal friction Angle; a, b, e, f are the parameters varying with the soil type and test method.

Accordingly, the shear intensity can be calculated according to the intensity shear formula, as shown in Equations (11), (12).

$$\tau = \sigma tan\varphi + c \tag{11}$$

$$\tau = \sigma tan(ew + f) + aw + b \tag{12}$$

Where τ is shear strength; σ is vertical pressure; w is water content; a, b, e, f are the parameters varying with the soil type and test method.

4.2.2 Change of shear intensity parameters at different cycles

For a sample given moisture content and dry density, the adhesion force decreases exponentially with increase of cycle times, using the following function with a high correlation coefficient. The calculation formula of cohesion is shown in Equation (13), and the calculation formula of internal friction Angle is shown in Equation (14).

$$c = re^{-qn} \tag{13}$$

Where c is the cohesion; n is the number of cycles; r and q are the parameters of the change with the sample properties.

$$\varphi = an^2 + bn + c \tag{14}$$

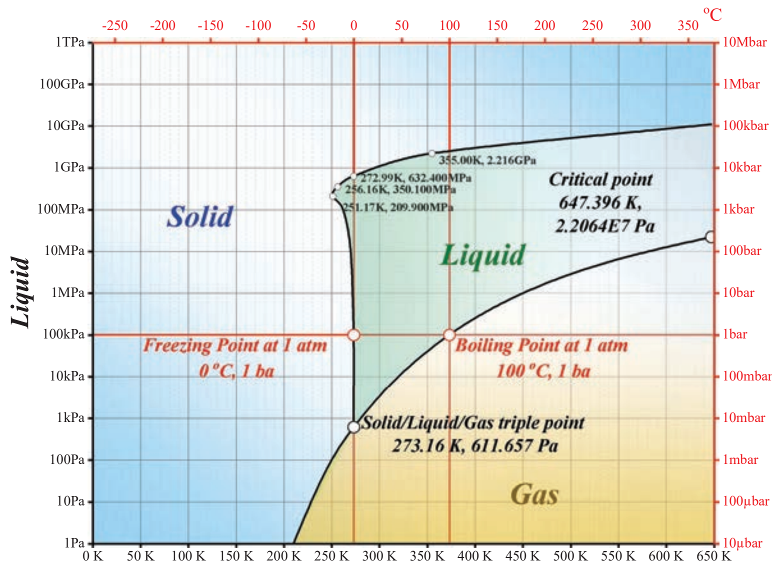

Figure 6 Parameter distribution of shear intensity.

In Equation (14), φ is the internal friction angle; n is the number of cycles; a, b, c are the parameters varying with the sample properties.

Accordingly, the shear strength can be calculated according to the intensity shear formula, as shown in Equations (15), (16).

$$\tau = \sigma tan\varphi + c \tag{15}$$

$$\tau = \sigma tan(an^2 + bn + c) + re^{-qn} \tag{16}$$

Where τ is the shear strength; σ is the vertical pressure; φ is internal friction Angle; c is cohesion; a, b, c, r, q are the parameters varying with the soil type and test method.

Figure 6 illustrates the distribution of shear intensity parameters, revealing a decreasing trend in shear strength as the number of cycles increases. Specifically, at a vertical pressure of 400 kPa, the initial shear strength of the soil is 279.048 kPa. Following a single cycle, the shear strength of the freeze-thaw sample decreases to 262.74 kPa, while the dry-wet sample's shear strength diminishes to 224.688 kPa. For the freeze-thaw dry-wet sample, the strength further reduces to 212.004 kPa. Upon three cycles, the shear strength of the freeze-thaw sample remains at 262.74 kPa, while the dry-wet sample's strength decreases to 228.32 kPa, and the freeze-thaw dry-wet sample's strength to 211.004 kPa. After five cycles, the shear strength of the freeze-thaw sample diminishes to 255.492 kPa, the dry-wet sample's strength shifts to 230.124 kPa, and the freeze-thaw dry-wet sample's strength decreases to 208.38 kPa. These trends persist across upper loads of 100 kPa, 200 kPa, and 300 kPa. It can be seen that compared with the freeze-thaw sample, due to the full effect of water in the dry and wet sample and the dry and thaw sample, the sample is more broken and scattered, and the shear strength of the sample is reduced faster.

In the design of the loess slope, the coupling effect of the freeze-thaw cycle and dry-wet alternations should be fully considered. When selecting slope reinforcement materials, materials with good resistance to freeze-thaw and dry-wet alternations should be prioritized to improve the slope's durability. In the construction process, compaction and drainage performance should be ensured to reduce the adverse influence of water on the loess slope. In slope monitoring and maintenance, we should pay close attention to the influence of freeze-thaw cycles and dry-wet alternations on slope stability and take corresponding strengthening and maintenance measures in time.

4.3 Change of Compression Characteristics at Different Water Content

Freeze-thaw and dry-wet cycling can profoundly influence the compressive properties of a soil sample. Theoretically, the compressibility of the soil is primarily influenced by its mineral composition, density, moisture content, and structural characteristics. Interactions between freeze-thaw and dry-moisture cycles modify the physical and mechanical properties of the soil, ultimately impacting its compressive behavior. This section mainly analyzes the test results from the compression coefficient and compression modulus. In order to make the data more practical, this paper explains the standard compression coefficient a_{1-2} and the standard compression modulus E_{1-2}.

Standard compression coefficient a_{1-2}: the calculation formula is shown in Equation (17), usually using the compression coefficient obtained when the pressure increases from $pi = 100$ kPa to $p_i + 1 = 200$ kPa to judge the compressibility of the soil. The greater the compression coefficient, the higher the compressibility of the soil.

$$a_{1-2} = \frac{e_{100} - e_{200}}{p_{200} - p_{100}} \tag{17}$$

e_i This is the pore ratio at a certain level of pressure.

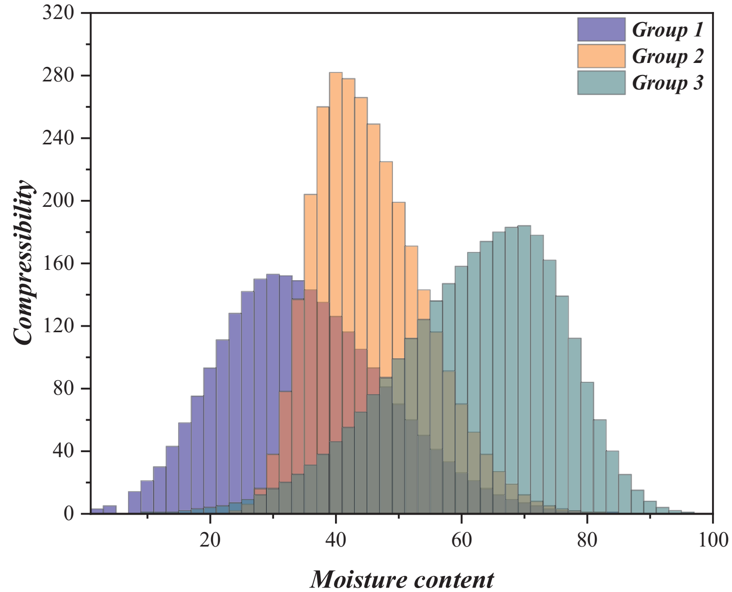

Figure 7 Change of compression characteristics under different water content.

Standard compression modulus E_{1-2}: The calculation formula is shown in formula (18). Usually, the compression modulus obtained when the pressure is increased from $p_i = 100$ kPa to $p_i + 1 = 200$ kPa is used to determine the compressibility of the soil. The greater the compression modulus, the lower the compressibility of the soil.

$$E_{1-2} = \frac{1 + e_0}{a_{1-2}} \tag{18}$$

Figure 7 shows the change of compression characteristics under different water content. The sample compression modulus E_{1-2} is negatively correlated with the water content. The greater the moisture content, the worse its ability to resist compression deformation, and with increase of moisture content, compression modulus E_{1-2} and the compression coefficient a_{1-2} change amplitude are smaller and smaller, which indicates that the close relationship between the compression deformation of the sample and the moisture content. Samples combined by freeze-thaw and dry and wet have more reduced compression modulus E_{1-2} than those treated by a single factor. The reasons are as follows: the consolidation compression of the sample is actually a process of drainage and exhaust, and soil particles.

Due to the increase of thickness, the expansion and deformation of the soil particles will increase the particle spacing, and the more sufficient the soil particles will be close to the compression. The freeze-thaw effect is similar to a compaction effect for the sample. When the ice crystals grow and the water migration and dispersion are melted, the particles are redistributed, the sample is loose, the integrity is weakened, and the compression modulus E_{1-2} is reduced. After the alternation of dry and wet samples, due to the expansion of water absorption and the contraction of water loss, with the constant change of water content of the test sample, the substrate suction is constantly added and unloaded, the connection between the particles is constantly destroyed, the large particles in the sample decompose, and the sample becomes looser. Due to the combined action, the weakening of soil is accelerated, which is reflected in the minimum compression modulus of freezing-thawing drying and wet soil E_{1-2}, which is easier to be compressed.

5 Conclusions

This paper, based on previous research work, with Lanzhou loess as the object, explores the freezing and dry and wet alternating effects and the influence of the loess mechanical properties, and the actual slope for a simplified model by exploring the slope in the effect of the temperature field and seepage field, for the basis of the slope stability of different slope exploration. The following conclusions are drawn:

(1) The freezing and thawing cycle is carried out repeatedly in the slope soil, and the freezing thickness of the soil layer deepens. The melting depth of the soil layer also increases, and over time, an isothermal closed circle is formed in the slope body.
(2) Due to the different slopes, causing different rainfall infiltration, Negative pore water pressure at the top of the slope rapidly increases from -176.52 kPa to -139.094 kPa; volume moisture content also increased rapidly from 14.11% to 16.63%; the negative pore water pressure of the slope foot increases to -76.33 kPa, The volume water content of 22.11%.
(3) With the alternation of the freezing and thawing cycle and dry and wet, the safety factor of the slope decreases continuously, and the slope safety factor decreases rapidly in the early stage. In addition, for the freeze-thaw slope, the slope is negatively correlated with the safety factor; that is, the more significant the slope, the lower the safety factor of the slope body. The safety coefficient of the 45° slope is maintained at a high level,

but compared with 51.3° and 60.9°, the early vibration of the 45° slope is relatively severe, and the amplitude is large. However, the dry and wet slope cognition is not comprehensive, and the slope stability is related to the seepage intensity and slope.

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