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Research on structural parameters of loess and its experimental determination method

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The structure of loess is an important physical property indicator. Just like grain size, moisture content and density, it also affects the physical and mechanical properties of loess. Based on the definition of the constitutive degree index, the definition of structural parameters was redefined. And conventional triaxial shear tests were conducted on undisturbed soil samples and remolded soil samples with different moisture contents and different dry densities. Firstly, the deformation characteristics and strength changes of the soil samples were analyzed. Then, based on the definition of structural parameters, the structural change laws of the soil were analyzed. Finally, the relationships between the structural properties and soil moisture, grain size and density were analyzed, thereby verifying that the newly proposed definitions of the structural parameters are reasonable.

KEYWORDS

soil, loess, structure, structural parameter, matric suction

1 Introduction

Loess is a loose deposit formed in the Quaternary period, which has a series of internal material composition and external morphological characteristics. It is different from other sediments in the same period and has certain regularity in its geographical distribution (Ding-Yi, 2001). The loess has wide distribution range, large thickness, intact strata and complex landform types, which greatly increase the complexity of loess engineering problems. The water sensitivity, large porosity and structure of loess cause its own collapsibility. This special engineering property leads to a variety of engineering problems and geological disasters in loess area. With the increasing frequency of economic activities and construction activities in the loess distribution area, higher requirements have been put forward for the study of loess engineering properties (Chen et al., 2025).

Due to the typical unsaturated and structural properties of loess, it often exhibits its own special properties, such as water sensitivity and seismic subsidence. These properties are closely related to the inherent structural properties of loess. Therefore, it is the realistic requirement of loess research to take loess structure as the root cause of its mechanical and engineering properties and to carry out further research to reveal the essential laws of the mechanical properties of loess.

The concept of soil structure was first proposed by Terzaghi (1973) and has been attached great importance by scholars since then. The structure of soil is a reflection of its physical state, which is another important physical property besides particle size, density, and humidity. The different combinations of mineral composition, particle characteristics, pore characteristics, and water content of soil result in different structural properties. Structure is the fundamental internal factor that controls the mechanical properties of soil, and the study of the structure of loess and its changes under the action of force and water plays an important role in the entire research object of soil mechanics (Terzaghi, 1973; Soga, 1994; Ding-Yi and Ji-Ling, 1999). The structure of soil, as an internal factor, is the dominant factor in the mechanical properties of soil. The anisotropy of soil and the collapsibility of loess are all manifestations of its structure (Cun-Li et al., 2006; Sheng-Jun et al., 2004; Sheng-Jun and Guo-Hua, 2008). The structural properties of soil are widely recognized as one of the essential characteristics of soil, and its related research is also considered as "the core problem of soil mechanics in the 21st century." The core objective of soil structural research is to establish a quantitative relationship between structural characteristics and macroscopic mechanical behavior, in order to achieve the goal of theoretical guidance for practical engineering. The premise of establishing this quantitative relationship is the quantitative characterization of soil structure, so the relevant research of structural quantification index has become the current research focus. The structure of loess is a comprehensive reflection of its material composition and particle arrangement. Taking into account the effects of various factors, a reasonable quantitative characterization of loess structure is the key to structural research and the prerequisite for studying loess structure and macroscopic mechanical properties (Chen and Chen, 2013). Therefore, it is necessary to conduct research on the relationship between structural and unsaturated characteristics from the perspectives of structural formation mechanisms (structural forces) and their strength (structural parameters), in order to provide a theoretical basis for solving engineering construction and geological disaster problems in loess distribution areas.

There have been many quantitative studies on the structural properties of soil by predecessors, but there have been relatively few studies on the structural properties of loess, a special type of soil. The global distribution of loess is widespread, therefore studying the structural characteristics of loess has important engineering practical significance. However, in the quantitative study of soil structure, predecessors mostly used the mechanical parameters or strength parameters of undisturbed soil, remolded soil and saturated soil to define the structural parameters. The process of obtaining structural parameters is too complicated, the workload is too large, and it is not convenient. Moreover, the calculation results of various methods are affected by test conditions and stress states, and can not reflect the stress state of loess and the relationship between loess structure and strength in the actual engineering situation. The definition of these parameters has certain limitations (Sheng-Jun et al., 2006; Guo-Hua and Shao, 2013; Zhi-Yan and Ding-Yi, 2009; Ya-Sheng et al., 2004; Ya-Sheng and Ding-Yi, 2005; Sheng-Jun et al., 2010).

Therefore, the purpose of this article is to propose a new structural quantification parameter that not only reflects the relationship between soil structure and strength, but also has a concise process and method with minimal workload. It is suitable for complex stress conditions and conforms to the stress state of loess in actual working conditions. Based on the definition of structural parameters, experimental research is conducted to analyze the deformation and strength characteristics of soil samples with different water contents under different confining pressures. The results of the triaxial test were calculated by the formula to obtain the size and change rule of the structural parameters of soil samples with different water contents and dry densities under different confining pressures. Finally, the rationality and stability of the structural parameters proposed in this paper were verified, proving that the parameters were feasible.

2 Materials and methods

2.1 Definition of structural parameters of loess under complex stress conditions

2.1.1 The establishment idea of structural parameters of loess under complex stress conditions

Most of the structural parameters that have been established so far describe the structural changes of soil during the deformation process, such as compression deformation process, triaxial and true triaxial shear deformation process. They are convenient to investigate the structural changes during loading. In actual working conditions, we also need metrics that can reflect the initial structural properties and strength characteristics of soil. Ya-Sheng and Ding-Yi (2005) proposed a parameter reflecting the initial structural properties of soil, structural index. This index is to further understand the basic physical properties of soil on the basis of particle size, density and moisture. However, this indicator has the following shortcomings: ①Because sand and soft clay are not convenient for uniaxial compression test, it is acceptable to use the structure index to study the structure of loess, but it is obviously insufficient to study the structure of sand and soft clay. ②The stress state of the soil studied by the constitutive index is a uniaxial, one-dimensional stress state, which does not match the actual stress state of the soil on the engineering site.

Therefore, this paper proposes a structural parameter m_τ through triaxial shear tests of undisturbed loess and saturated remodeled loess from the perspective of shear resistance that can reflect soil structure and convenient testing, following the idea of comprehensive structural potential. This parameter is defined by the ratio of shear strength of index loess and saturated remolded loess. It can not only reflect the strength characteristics of soil, but also apply to complex stress states.

$$m_\tau = \frac{\tau_o}{\tau_{rs}} \tag{1}$$

In the formula 1, τ_o represents the shear strength of undisturbed soil under certain stress conditions, τ_{rs} represents the shear strength of remolded soil under the same stress conditions.

Due to the inability to directly obtain the shear strength value of the specimen through triaxial shear testing, in order to directly use the test data for the calculation of structural parameter m_τ and enhance the applicability and convenience of structural parameters, formula 1 will be derived.

According to Coulomb's law, the shear strength of soil τ_c is:

$$\tau_c = c + \sigma_f \tan\varphi \tag{2}$$

In the formula 2, c is the cohesive force (kPa), φ is the internal friction angle (°), and σ_f is the normal stress on the shear failure surface (kPa). The calculation formula is as follows:

$$\sigma_f = \frac{1}{2}(\sigma_1 + \sigma_3) + \frac{1}{2}(\sigma_1 - \sigma_3)\cos 2\alpha_f \tag{3}$$

In the formula 3, σ_1 represents the major principal stress, and σ_3 represents the minor principal stresses (kPa); α_f is the angle between the shear failure surface and the surface under the action of the large principal stress σ_1, which is called the failure angle.

$$\alpha_f = \frac{\pi}{4} + \frac{\varphi}{2} \tag{4}$$

By substituting formula 4 into formula 3, the following equation can be obtained:

$$\sigma_f = \frac{1}{2}(\sigma_1 + \sigma_3) - \frac{1}{2}(\sigma_1 - \sigma_3)\sin\varphi \tag{5}$$

Substitute formula 5 into formula 2 to get the following equation:

$$\tau_c = c + \left[\frac{1}{2}(\sigma_1 + \sigma_3) - \frac{1}{2}(\sigma_1 - \sigma_3)\sin\varphi\right]\tan\varphi \tag{6}$$

By substituting formula 6 into formula 1, we can obtain the formula 7:

$$m_\tau = \frac{2c_o + [(\sigma_{1o} + \sigma_{3o}) - (\sigma_{1o} - \sigma_{3o})\sin\varphi_o]\tan\varphi_o}{2c_{rs} + [(\sigma_{1rs} + \sigma_{3rs}) - (\sigma_{1rs} - \sigma_{3rs})\sin\varphi_{rs}]\tan\varphi_{rs}} \tag{7}$$

The values of major and minor principal stresses σ_1 and σ_3 and strength parameters c and φ in formula 7 can be obtained directly through triaxial tests, so formula 7 can be used as a calculation formula for structural parameters m_τ of loess under complex stress conditions.

Formula 7 can be used as the calculation formula of structural parameter m_τ, and from this formula, the following conclusions can be drawn. The stronger the connection between the original soil particles, the greater the loss of loess strength caused by the disturbance, and the more unstable the arrangement of soil particles. After immersion and disturbance, the greater the strength loss caused by the destruction of soil structure under the action of force, the more unstable the arrangement of soil particles. The greater the strength of the undisturbed soil, the greater the m_τ the greater the influence of disturbance and immersion, the greater the m_τ. The changes of τ_o and τ_{rs} can be sensitively reflected in the changes of m_τ.

2.1.2 The superiority of structural parameters of loess under complex stress states

The newly defined structural parameter m_τ under complex stress is based on the shear strength of the soil, so it describes the structure of the soil at the ultimate failure state. It has the following advantages compared to existing structural parameter definitions.

(1) According to the existing definition of structural parameters, many experimental results indicate that the maximum value of structural strength is not at the initial state. This obvious contradiction suggests that the currently defined structural parameters cannot fully reflect the structure of the soil. The new definition uses the intensity ratio instead of the coefficient ratio, making the concept clearer than the previous definition of the product of two coefficients. In addition, the structural parameter expressed by the strength parameter indicates that it is a material constant and a comprehensive reaction of the strength of soil materials, so the definition is more standardized and suitable for a wider range.

(2) Any type of soil has a primary structure and certain structural strength in any state, but currently the vast majority scholars agree that saturated remolded soil does not have structural strength. The new definition uses the strength parameters of remolded saturated soil to replace the strength parameters of saturated soil and remolded soil, which not only breaks through the limitation that saturated remolded soil does not have structural strength, but also lifts the structural stability and structural variability of soil at one time, which makes the test conditions simpler and the test sample size smaller.

(3) The new definition replaces uniaxial strength with triaxial strength, which is suitable for complex stress states. Its testing method is more flexible and can be measured using triaxial shear tests, direct shear tests, and even *in-situ* tests.

(4) The new definition can also study the structural properties of soils with weak structural properties such as sand and soft clay, which proves that the problems studied by the new definition are more comprehensive and extensive.

(5) The new definition introduces stress states, which can be directly used for establishing constitutive relationships. Applying this parameter to engineering can consider changes in stress state, as structural parameters vary at different locations.

(6) The calculation results of existing structural parameters are all affected by experimental conditions, stress and strain states, and do not reflect the relationship between soil structure and strength, which has certain limitations. The newly defined structural parameters break this limitation and capture the essence of the problem. The fundamental characteristic of soil structure is strength. Factors that affect soil structure, such as particle size distribution, arrangement method, compactness, and water content, can all be reflected by strength parameters. Therefore, using shear strength is more reasonable than other definitions.

2.2 Basic properties of experimental soil

The soil samples were collected from a construction site in Pucheng County, Weinan City, Shaanxi Province, with developed vegetation at the sampling site. Using the exploratory well sampling method, dig the exploratory well to approximately half a meter below the required sampling depth, then manually sample at a depth of 1 m in the sidewall, and then expand the diameter of the exploratory well to continue sampling. Wrap the undisturbed loess with shockproof bubble wrap on the outside and seal it to prevent moisture loss. In the process of sampling and packaging, the disturbance of the sample is avoided as much as possible, and the undisturbed structure of the soil sample is maintained to the maximum extent. Mark the upper surface of the soil sample on the wrapped soil block to determine the direction of the soil sample during testing and

FIGURE 1
The exploration well.

FIGURE 2
The undisturbed soil sample.

avoid the influence of anisotropy. This time, the original soil samples were taken at different depths, the depth of the soil was taken from 3 m, and then the deeper soil samples were taken at 1 m intervals, for a total of 5 different depths of the undisturbed soil. The soil sample taken was light yellowish-brown, belonging to Q_3 loess, with worm holes and plant root holes scattered, accompanied by snail shells, plant roots and a few stones. The exploration well and the undisturbed soil samples collected are shown in Figures 1, 2.

According to the Standard for geotechnical testing method (GB/T50123-2019) (Ministry of Water Resources, 2019), the physical properties of soil samples at each depth were determined, and the test results are shown in Table 1.

The particle size distribution of the soil samples at depths of 3 m, 5 m, and 7 m was determined by sieve analysis and densitometer methods, and the particle size composition of the test soil samples is shown in Table 2. The particle size of the soil

TABLE 1 Physical property indexes of weinan loess.

Depth of soil extraction (m)	Relative density (g/cm^3)	Water content (%)	Liquid limit (%)	Plastic limit (%)	Plasticity index	Density (g/cm^3)	Dry density (g/cm^3)	Void ratio
3.0	2.70	9.2	30.6	18.3	12.3	1.48	1.35	1.00
4.0	2.70	11	27.6	16.8	10.8	1.57	1.41	0.92
5.0	2.70	17	34.6	16.6	18	1.66	1.42	0.91
6.0	2.70	16.6	28	17	11	1.59	1.36	0.92
7.0	8.6	39.9	17.5	12.4	1.32	1.49	1.28	1.12

TABLE 2 Grain size composition of weinan loess.

Percentage composition (%)				Classification by particle composition
Depth of soil extraction (m)	Clay particles (mm) <0.005	Silt particles (mm) 0.005 ~ 0.075	Sand particle (mm) 0.075 ~ 2	
3 m	18.97	80.28	0.75	Silty clay
5 m	17.68	80.82	1.5	Silty clay
7 m	19.8	77.35	2.85	Silty clay

TABLE 3 Mineral Composition Content of weinan Loess.

Mineral types	Quartz	Alkali	Feldspar	Plagioclase	Dolomite	Hematite	Clay mineral
Content (%)	41.2	2.6	13.5	18.5	2.4	0.7	21.1

sample is mainly composed of silt particles, with a content of over 70%, followed by clay particles, and sand particles have the lowest content.

The solid particles in soil are composed of minerals, and the mineral composition is also an important factor affecting the engineering geological properties of soil. The mineral composition mainly includes primary minerals, secondary minerals, and organic matter. The mineral composition of undisturbed loess was determined by X-ray diffraction test, and the results are shown in Table 3.

It can be seen from the test results that the loess in this area is mainly primary minerals, followed by secondary minerals, and the degree of weathering is not high. The content of primary minerals accounts for 78.9%, and it is mainly quartz and feldspar, with strong weathering resistance. Calcite, the most common mineral in natural $CaCO_3$, was present in high levels in this soil sample, and the calcite crystals cemented the soil particles together and increased the strength of the soil when the soil had low water content. The soil samples contained traces of hematite, a free oxide with excellent cementing properties, but in small amounts. The total content of soluble salts in this loess was measured to be 0.08%, which is very low, and the $CaCO_3$ content was 17.9%, which is more consistent with the calcite content in the mineral composition analysis. The higher $CaCO_3$ content will result in stronger cementation between particles, thus improving the structural strength of the soil samples.

2.3 Experiment scheme

According to the Standard for geotechnical testing method (GB/T50123-2019) (Sheng-Jun et al., 2010), the shear strain rate for the test is 0.5%/min, which is 0.4 mm/min. The test is stopped when the shear strain reaches 20%. The experiments are SY10-2 strain controlled triaxial apparatus and SJ-1A triaxial shear apparatus. In this experiment, the undisturbed loess was taken as the research object, and the undisturbed soil was cut into the cylindrical soil sample ($d = 39.1$ mm, $h = 80$ mm) required by the test according to the Standard for Soil Test Method (GB/T50123-2019).

2.3.1 Test scheme under different confining pressure conditions

To study the deformation and strength characteristics as well as the variation rules of structural parameters of undisturbed and remodeled loess under different confining pressures. The experiment adopts the method of controlling variables, which requires ensuring the same soil source, taking undisturbed soil samples with the same dry density and moisture content, and preparing remodeled soil samples with the same specifications and conditions. The conventional triaxial shear tests were loaded with confining pressures of 100 kPa, 200 kPa, 300 kPa, and 400 kPa confining pressure, and the test conditions were consolidation without drainage.

2.3.2 Test scheme under different moisture contents

To study the deformation and strength characteristics as well as the variation rules of structural parameters of undisturbed and remodeled loess with different moisture contents. The experiment adopts the method of controlling variables to ensure that the soil samples obtained have the same source and dry density. Different moisture contents were formulated for the undisturbed and remodeled samples used in the study, and the values of moisture contents from air dried to saturated condition of the soil samples are shown in Table 4. The undisturbed soil with a moisture content of 6% was prepared using a natural drying method specific to the original state of the soil. The undisturbed samples with moisture contents of 16%, 21%, 26%, and 31% were prepared using a natural titration method for undisturbed soil. Initially, water is introduced to the sample, which is subsequently placed in a humidification chamber for over 24 h to facilitate uniform and free diffusion of moisture. The remodeled sample is prepared using the compaction method under controlled conditions of dry density and moisture content. The saturated sample is obtained through the vacuum saturation technique.

TABLE 4 Moisture content values of loess samples.

Moisture content (%)	Natural moisture content (%)	Moisture content (%)	Moisture content (%)	Moisture content (%)	Moisture content (%)	Saturated moisture content (%)
6	11	16	21	26	31	36

TABLE 5 Dry density values of loess samples.

Dry density (g/cm^3)	1.35	1.41	1.42	1.36	1.28
Depth of soil extraction (m)	3	4	5	6	7
Natural moisture content (%)	9.2	11	17	16.6	16.7

2.3.3 Test scheme under different dry densities

To study the deformation and strength characteristics as well as the variation rules of structural parameters of undisturbed and remodeled loess with different dry densities. The test was conducted using the controlled variable method to ensure that the soil samples were from the same source and moisture content. Undisturbed soil samples were collected from five locations at different depths (different dry densities) and then remodeled soil samples with the same moisture content and dry density were prepared as shown in Table 5. The initial water content of the undisturbed loess at different depths is different, so it is necessary to adjust the water content of the loess samples as described in the previous section.

The number of samples required for this test is shown in Table 6.

In order to ensure the accuracy of the test, considering the inevitable errors, 5 undisturbed samples and 5 remolded samples were prepared for backup.

3 Results

3.1 The variation law of shear strength index

Given that the structural parameters presented in this paper are defined in relation to the shear strength of the soil, it is essential to assess the variations in soil strength prior to analyzing structural changes. Numerous factors influence the shear strength index (cohesion and internal friction angle) of soil, with parameters such as soil structure, density, and moisture content being closely associated with this index (Ya-Sheng, 2005). Consequently, this section examines the impact of variations in moisture content and dry density on the shear strength parameters of soil through triaxial shear testing.

The strength parameters of undisturbed and remolded samples with different water contents obtained through triaxial shear tests are shown in Tables 7, 8.

In order to visually display the variation pattern of strength parameters with moisture content, the data is plotted as shown in Figure 3.

It can be seen from Figure 3A that the cohesion of the soil sample decreases exponentially with increasing water content. Macroscopically, this phenomenon is due to the increase in water content causing the soil to become softer and the strength of the sample to weaken. From a microscopic perspective, the connecting forces between soil particles are very complex, with not only gravitational but also repulsive forces. When the overall gravitational force exceeds the repulsive force, it will exhibit gravitational force; otherwise, it will exhibit repulsive force. Water molecules exist in soil particles in the form of bound water and free water. The water content in soil varies, and the form of water present in soil particles also varies. When the water content of the loess sample is low, the water in the soil mostly exists in the form of bound water in the soil particles, and bound water is one of the sources that determines cohesion. Water molecules have a binding effect on soil particles, resulting in a greater attraction between particles. When the moisture content in the soil sample increases, the bound water film becomes thicker, and the strongly bound water in the soil gradually becomes weakly bound water, resulting in a decrease in the degree of connection and the appearance of free water in the soil (Wu et al., 2023). At this time, the lubrication between soil particles is enhanced, and the biting force and friction force between soil particles between soil particles are significantly reduced. In addition, the increase in water content in the soil dissolves the bonding materials and salts between soil particles, reducing their bonding ability. These factors will lead to the reduction of the cohesion of soil. Jiang (2020) also obtained similar results. Through shear tests on remolded soil, it can be seen that water content has a relatively significant impact on the cohesion of soil, and the increase of water content would lead to a rapid decrease in cohesion.

It can be seen from Figure 3B that the internal friction angle decreases linearly with increasing water content. When the moisture content of the loess sample increases, the free water in the soil particles will increase, which will enhance the lubrication effect between the soil particles and reduce the biting force and friction force between the soil particles. In addition, free water will fill the pores between the particles in the soil, which will dissolve the cementing materials and salts between the particles, weaken the connection between the soil particles, and ultimately resulting in a decrease in the friction angle within the soil. Additionally, when the water content is low, a sliding shear plane will appear when the sample is shear damaged, and the degree of concaveness on the shear plane is obvious, which increases the sliding friction force and also increases the internal friction angle of the soil.

According to the mechanism of unsaturated soil cohesion, cohesion c is mainly composed of original cohesion, solidified cohesion, and capillary cohesion. Based on the relationship between these three factors and moisture content, from the perspectives of wet suction and structural suction, the cohesive force gradually

TABLE 6 **Statistics of the number of experimental samples.**

Sample types	Relative density (g/cm^3)	Water content (%)	Confining pressure (kPa)	Total number of samples
Undisturbed soil	1.28, 1.35, 1.36、1.41, 1.42	36, 31, 26, 21, 16, 11, 6	100, 200, 300, 400	5 × 4 + 7 × 4
Remolded soil	1.28, 1.35, 1.36, 1.41, 1.42	36, 31, 26, 21, 16, 11, 6	100, 200, 300, 400	5 × 4 + 7 × 4

TABLE 7 **Shear strength parameters of undisturbed samples in triaxial test.**

Moisture content (%)	6	11	16	21	26	31	36
c (kPa)	33.9	29.5	27.9	20.6	15.7	12.9	10.8
φ (°)	30.01	29.7	29.24	28.13	26.71	26.16	25.72

TABLE 8 **Shear strength parameters of remolded samples in triaxial test.**

Moisture content (%)	6	11	16	21	26	31	36
c (kPa)	25.4	23.3	21.1	15.8	12.8	9.84	7.9
φ (°)	23.17	22.73	21.56	19.8	17.84	17.32	16.35

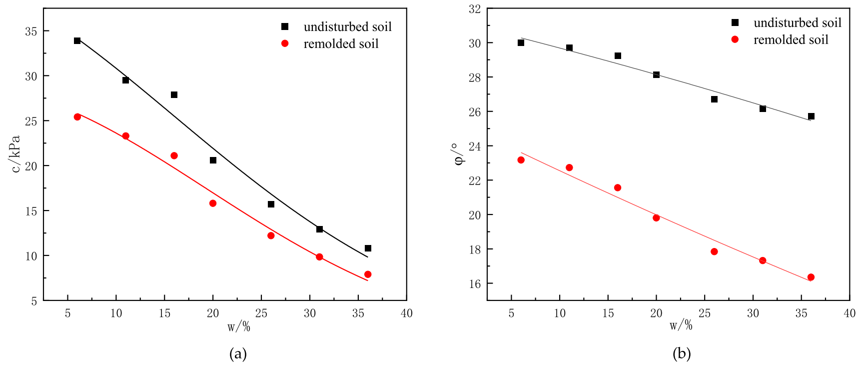


FIGURE 3
The relationship between c and φ and moisture content of loess samples. **(A)** Relationship curves between cohesion and water content of loess samples. **(B)** Relationship curves between internal friction angle and water content of loess samples.

decreases monotonically with the increase of moisture content (Chang-Jiang, 2006; Peng-Cheng et al., 2012a; Peng-Cheng et al., 2012b), which is consistent with the results of triaxial tests. The internal friction angle is mainly generated by the surface friction force of soil particles and the biting force between soil particles. As the moisture content increases, due to the lubricating effect of water, the surface friction and biting force between soil particles decrease, resulting in a gradual decrease in the internal friction angle. Due to the relatively small influence of changes in moisture content on the relative sliding between soil particles, the amplitude of changes in internal friction angle is smaller than that of internal cohesion.

Furthermore, based on the unsaturated soil theory, when the dry density of the soil sample remains constant, both the total suction and matric suction of the soil sample are negatively correlated with an increase in moisture content. This phenomenon arises from the fact that the primary determinant of suction in unsaturated clay is the tension of liquid surface. When the soil is highly dry, water present between soil particles adopts a curved liquid surface configuration, leading to direct contact between particles and the formation of a skeletal structure. At this stage, to establish a water film, the tension of local liquid surface reaches its maximum value. When the soil moisture content is low, more water in the soil forms not only the capillary water but also the free water due to the increase in water content. Under the influence of surface tension, gravitational water is entirely reabsorbed into the interstitial spaces between particles, resulting in the formation of a water film of considerable thickness. At this stage, the interaction between particles transitions from a framework connection to the water film.

TABLE 9 Shear strength of undisturbed soil in triaxial test.

Moisture content (%)	6	11	16	21	26	31	36
Normal stress (kPa)	Shear strength (kPa)						
100	91.66	86.54	83.88	74.06	66.02	62.02	58.47
200	149.42	143.58	139.86	127.52	116.33	111.14	106.64
300	207.17	200.62	195.84	180.99	166.65	160.26	154.81
400	264.93	257.66	251.82	234.45	216.97	209.38	202.98

TABLE 10 Shear strength of remolded soil in triaxial test.

Moisture content (%)	6	11	16	21	26	31	36
Normal stress (kPa)	Shear strength (kPa)						
100	68.2	65.19	60.61	51.8	44.98	41.02	37.24
200	111	107.08	100.12	87.8	77.17	71.21	66.57
300	153.79	148.98	139.64	123.81	109.35	103.39	95.91
400	153.79	148.98	139.64	123.81	109.35	103.39	95.91

When the soil moisture content is elevated, both pore water and gravitational water progressively increase, resulting in the saturation of interparticle voids with water (Hang et al., 2022). As the surface tension of the meniscus increases, the thickness of the water film also rises. At this stage, interparticle tensile forces approach zero, facilitating connectivity between the aqueous phase and gas phase. When the voids between soil particles are entirely saturated with water, the soil reaches a high or fully saturated state. At this juncture, the soil particles make contact through a continuous water film, resulting in zero matrix suction. Consequently, small air bubbles can migrate along with the water. Matrix suction is a critical factor influencing the shear strength of unsaturated soils. As water content increases, matrix suction correspondingly decreases, which in turn affects the soil's shear strength and leads to a reduction in its overall shear capacity.

3.2 The variation law of shear strength

The shear strength of both undisturbed and remolded soil samples at varying moisture contents, as determined through triaxial shear testing, is detailed in Tables 9, 10.

To effectively illustrate the relationship between shear strength and moisture content, the variations in shear strength of both undisturbed l and remolded loess samples obtained from triaxial shear tests were plotted against moisture content, as depicted in Figure 4. Additionally, Figure 5 presents the trend of shear strength for samples with varying moisture contents in relation to principal stress.

It can be seen from Figures 4, 5 that when the dry density of the soil sample is kept constant, as the water content increases, the trend of change in the undisturbed soil sample and the remolded soil sample is similar. The shear strength in each principal stress condition shows a downward trend. The principal stress has a significant influence on the shear strength when the water content is small. The influence of the principal stress on the shear strength becomes smaller as the water content increases. When the water content of the soil sample reaches the saturated water content, the shear strength becomes very flat with the change of the principal stress. The degree of change in shear strength with water content is large when the normal stress is small, and the degree of change is not significant when the principal stress is large.

Fundamentally, this phenomenon arises from the large pores and open structure inherent to loess. At lower moisture content, it retains a loose cohesive structure due to interparticle attraction, characterized by a higher air-to-water ratio within the soil. The water film on the surface of soil particles is relatively thin, resulting in stronger interparticle connections that are less susceptible to shear failure. As moisture content increases, the water film thickens, thereby increasing the distance between particles and diminishing their mutual attraction. Additionally, increased moisture dissolves soluble salts that contribute to cohesion in the soil and softens cementing materials. This leads to a significant reduction in the friction coefficient between particles and consequently diminishes the shear resistance of loess samples. Zhan-Fei and Yan-Rong (2001) research indicates that free water presence reduces gravitational forces among particles while altering the effects of applied vertical pressure. This observation underscores that as moisture content rises, the shear strength of loess samples declines.

Based on the unsaturated theory analysis, the shear strength of soil is mainly composed of the bonding force and the occluding

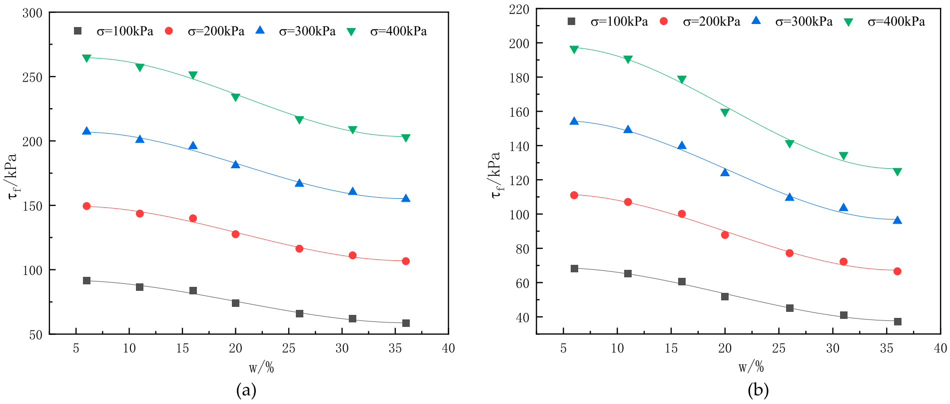


FIGURE 4
The relationship between shear strength and principal stress of soil samples with different moisture contents. **(A)** Undisturbed soil. **(B)** Remolded soil.

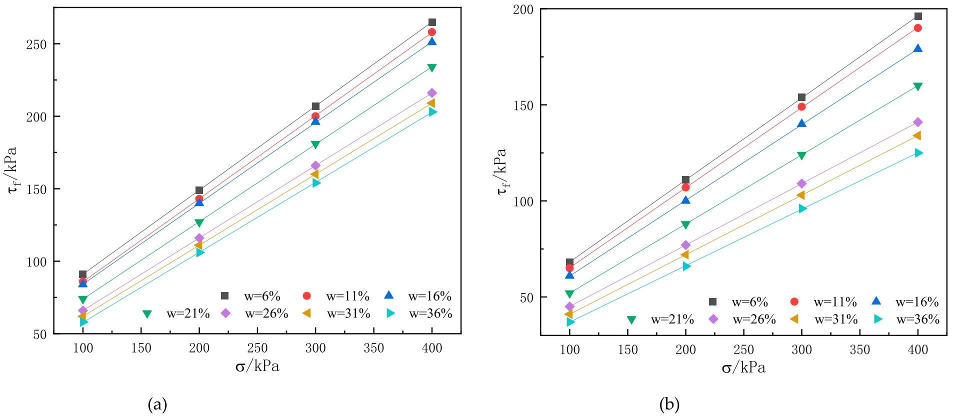


FIGURE 5
The relationship between shear strength and principal stress of soil samples with different moisture contents. **(A)** Undisturbed soil. **(B)** Remolded soil.

force between soil particles, among which the bonding force includes van der Waals force, double electric layer force and cementation force, etc. The above forces are closely related to the size, spatial arrangement and intergranular connection of soil particles (Sheng-Jun et al., 2014). When soil pores are filled with water, water film is formed between adjacent soil particles and surface tension is generated. At this time, the soil particles will be affected by both pore water pressure and pore air pressure, and the difference between the two is defined as matrix suction in unsaturated soil mechanics. The magnitude of this force is closely related to the moisture content between the pores of soil particles, and is one of the important factors affecting the shear strength (Mao-Tian et al., 2006). Numerous experimental studies have shown that under the action of matric suction, the shear strength of unsaturated soil is generally greater than that of saturated soil (Mohamed et al., 2006; Cokcae and Tilgen, 2010). The large particles in the clay are formed by the agglomeration. When the matrix suction increases, the water between the agglomeration is first drained. At this time, the agglomeration particles shrink, bringing the nearby soil particles close to each other. When the matric suction decreases, the agglomerations first absorb water and expand, causing the soil pores to increase. The main reasons for the increase in shear strength of agglomerations are the increase in their own strength after dehydration and the increase in van der Waals forces between clay particles.

3.3 Results of triaxial shear test

3.3.1 Analysis of stress-strain characteristics of undisturbed loess

According to the test results, the stress-strain relationship of undisturbed loess with different moisture contents under the same confining pressure is summarized. Figure 1 shows the stress-strain curves of undisturbed loess. As shown in Figure 6, point A (red point) marked in the stress-strain curve with a moisture content of 6% represents the endpoint of the approximate elastic deformation stage, and point B (blue point) represents the peak strength.

The following results can be obtained from the Figure 6.

(1) The stress-strain curve is softening type, when the moisture content of the sample is 6%. In the initial stage of load action,

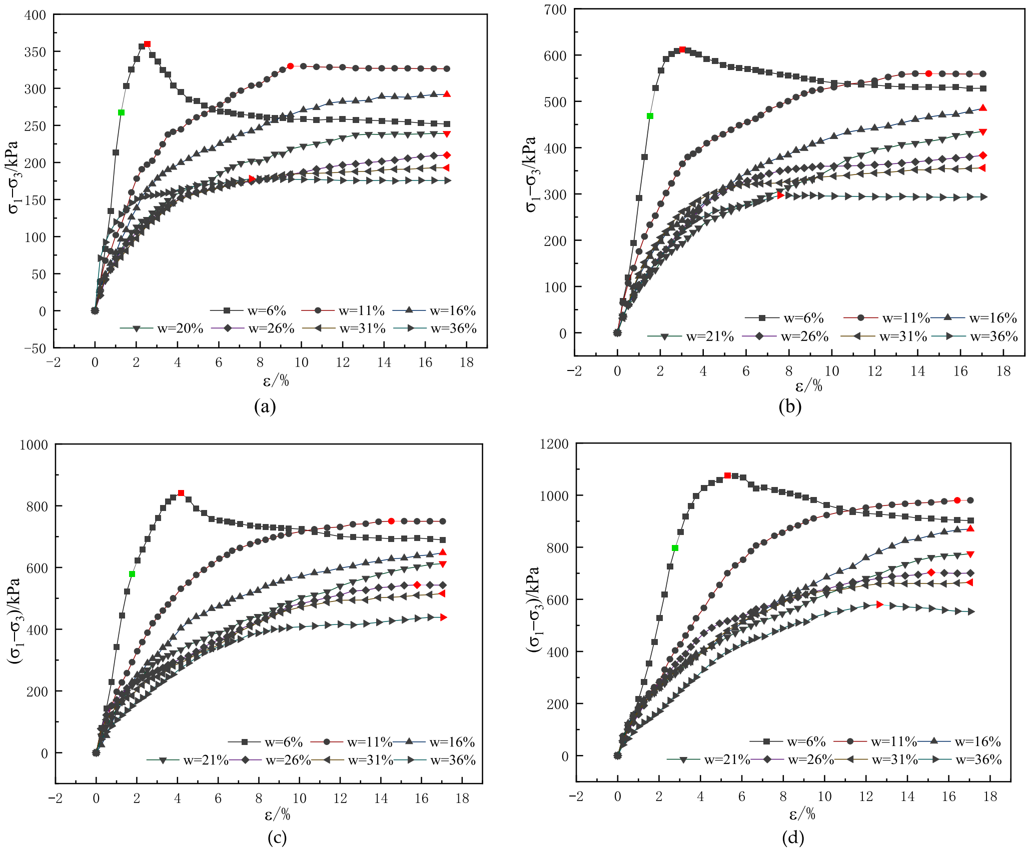
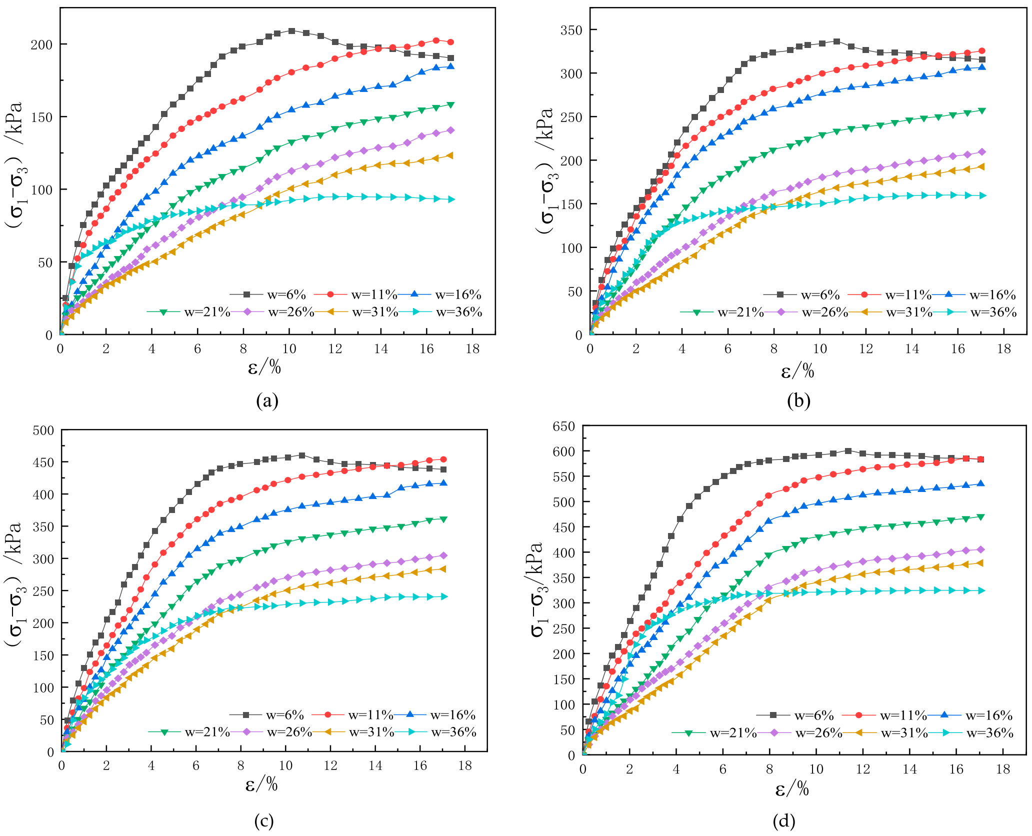


FIGURE 6
Stress-strain curves of undisturbed soil with different moisture contents in triaxial test. **(A)** Confining pressure = 100 kPa. **(B)** Confining pressure = 200 kPa. **(C)** Confining pressure = 300 kPa. **(D)** Confining pressure = 400 kPa.

the stress rapidly reaches its peak within a small strain range (0%–2%) and then rapidly decreases. When the strain reaches 12%, the stress remains basically stable. As the increase of moisture content, the curves gradually changed from softening type to hardening type. The higher the moisture content of the soil sample, the smaller the stress required to achieve the same strain. The peak strength decreases with the increase of moisture content. As the moisture content increases, the strain corresponding to the peak strength of the soil sample shows an increasing trend. And the slope of the curve in the approximate elastic deformation stage of high moisture content samples is significantly smaller than that of low moisture content samples.

(2) When the moisture content is 6%, compared to high moisture content soil samples, the bonding effect between soil particles is stronger and the peak strength is higher. After the stress reaches its peak strength, the soil structure is destroyed, and the frictional force begins to take effect, but it is far less than the strength loss caused by structural failure, so the principal stress difference decreases rapidly. As the moisture content increases, the cementation and friction between particles are weakened, resulting in the overall reduction of sample strength. When the moisture content increases to 16%, the peak strength of the sample significantly decreases, and the residual strength also decreases due to the decrease in friction. But the influence of moisture content on friction has become weak. When the samples with water content of 16% and 20% reach the peak strength, the strength loss caused by structural failure is similar to the frictional force, and the principal stress difference is reduced less. The stress-strain curve of the samples gradually changes to the hardening type and shows a weak softening type. However, the frictional effect between particles completely compensates for the strength loss caused by structural failure, when the moisture content continues to increase to 31%. And the stress-strain curve shows a weak hardening type.

(3) In addition, as the moisture content increases, the plastic deformation generated by the sample before failure gradually increases due to the weakening of the bonding effect between particles, resulting in a rightward shift of the strain corresponding to the peak strength. On the one hand, the weakening of the connecting effect will lead to a decrease in the stress corresponding to the end point of the approximate elastic deformation stage. On the other hand, when the bonding effect is weakened, the failure of the connection in this stage will increase, and the deformation will increase. The result of the combined effect of the above two factors is that with the moisture content increases, the stress corresponding to the end point of the approximate elastic deformation stage of the sample decreases, and the slope of the curve at this stage decreases.



(a)
(b)
(c)
(d)

FIGURE 7
Stress-strain curves of remolded soil with different moisture contents. **(A)** Confining pressure = 100 kPa. **(B)** Confining pressure = 200 kPa. **(C)** Confining pressure = 300 kPa. **(D)** Confining pressure = 400 kPa.

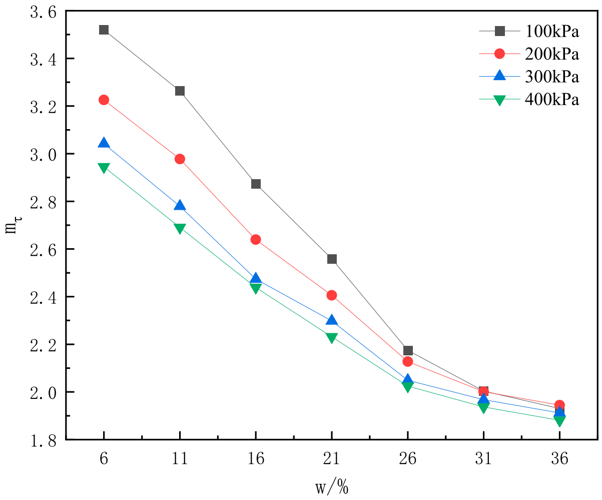


FIGURE 8
Variation curves of structural parameters with water content.

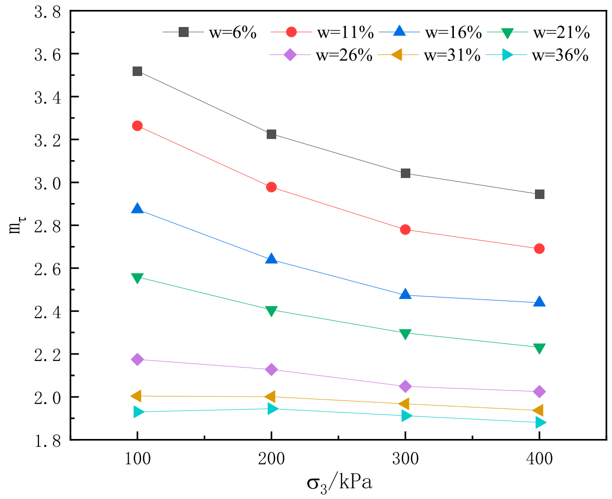


FIGURE 9
The variation curves of structural parameters with confining pressure under the same water content.

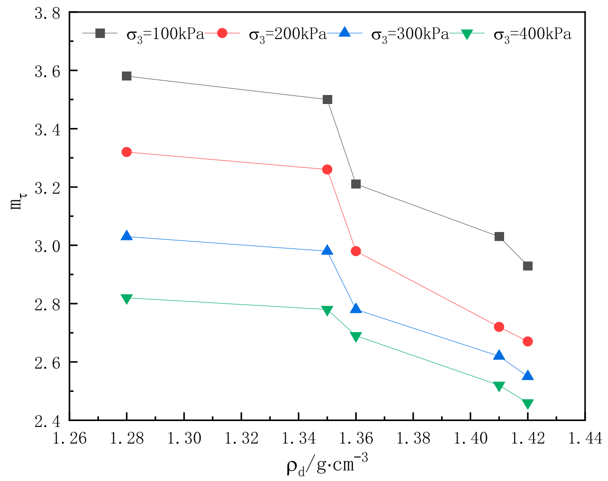


FIGURE 10
The variation curves of structural parameters with dry density.

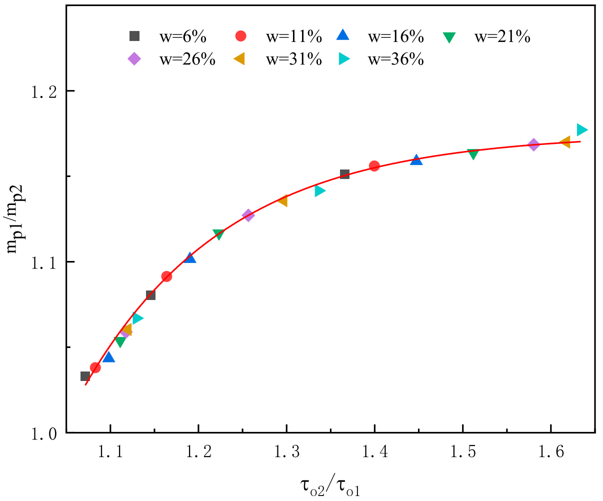


FIGURE 12
The relationship curve between the ratio of structural parameters and the inverse ratio of shear strength.

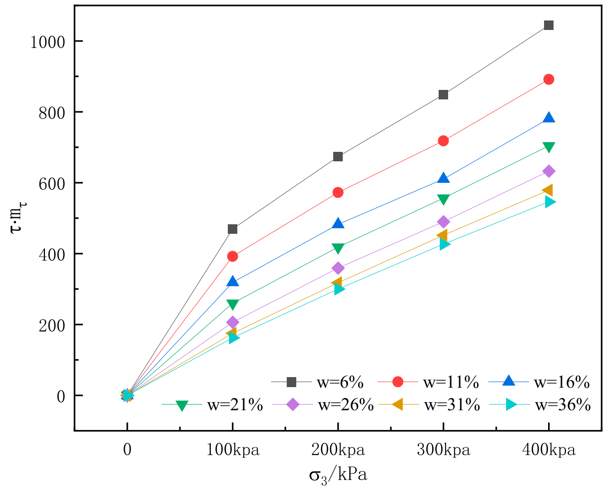


FIGURE 11
$\tau \bullet m_\tau - P$ variation curve of soil samples with different water contents.

TABLE 11 Values of $\sigma_1 - \sigma_3$, c, φ and m_τ of soil samples with different water contents.

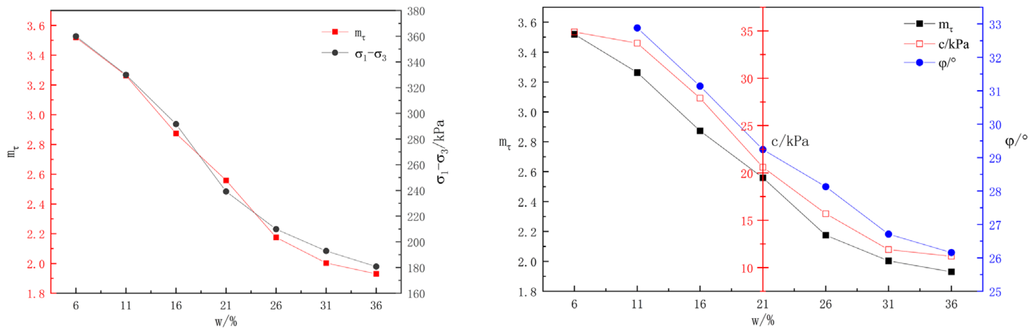
Number	w (%)	q_{max}(kPa)	c(kPa)	φ(°)	m_τ
1	6	360	34.9	32.88	3.52
2	11	330	33.7	31.14	3.26
3	16	291.6	27.9	29.24	2.87
4	21	239.2	20.6	28.13	2.56
5	26	209.9	15.7	26.71	2.17
6	31	192.9	11.8	25.64	2.003
7	36	180.8	11.2	23.76	1.93

3.3.2 Analysis of stress-strain characteristics of remolded loess

It can be seen from Figure 7 that the stress-strain relationship curves of remolded loess with different moisture contents, and the following conclusions can be obtained from them.

(1) When the confining pressure is 100 kPa, the stress-strain curves of the reconstructed soil sample are similar to that of the undisturbed soil sample, but the peak strength is smaller than that of the undisturbed soil sample. When the water content is 6%, the curve presents strain softening type, and the change of residual strength gradually slows down with the increase of confining pressure. As the increase of water content, the curve gradually transforms into strain hardening type.

(2) With the same confining pressure, the higher the moisture content of the remolded soil, the smaller the value of its stress-strain curve, and the slower the upward trend of the initial section. It can be seen that an increase in moisture content can weaken the structural strength of the remolded soil, and there is a negative correlation between these two parts. This is because the increase of moisture content thickens the water film between soil particles, and the cementing material dissolves. This will weaken the intergranular connection and damage the soil sample structure. At the same time, when the moisture content is large, the water film which plays a lubricating role in the soil particles is thickened, which weakens the mechanical biting force and double electric layer effect between the soil particles, and significantly reduces the structural strength. It can be concluded that there is a negative correlation between the shear strength of remolded soil samples and their moisture content. With the increase of moisture content, the curve gradually transforms into strain hardening type.



(a)

(b)

FIGURE 13
(A): The variation curves of structural parameters and peak strength with moisture content Title of **(B)**: The variation curves of structural parameters and strength parameters with moisture content.

By summarizing the results of the triaxial shear test above, the structural changes of loess during the loading process can be obtained. When the confining pressure is low, the principal stress difference corresponding to the coaxial strain is taken on the stress-strain curves of the undisturbed and remolded samples, which has the characteristic that the principal stress difference of the undisturbed soil is greater than that of the remolded soil, and the principal stress difference of the remolded sample is greater than that of the saturated undisturbed soil. When the confining pressure is high, the confining pressure has completely destroyed the structure of undisturbed soil, then the principal stress difference of undisturbed soil is less than that of remolded soil, and the principal stress difference of remolded soil is still greater than that of saturated undisturbed soil. When the confining pressure is small, the damage to the undisturbed soil structure is weak, and it has a greater structural strength. When the confining pressure increases, the structure of the undisturbed soil is destroyed during consolidation, and the structural strength decreases. At the same time, the pore distribution of the undisturbed samples is not uniform in the process of natural deposition, and the cementation is destroyed under high confining pressure. During the preparation process, the remolded sample forms a unique and complete secondary structure, so the principal stress difference of the remodeled soil with coaxial strain under high confining pressure may be larger than that of the original soil. There is no water film effect in the saturated sample, and the cementing material between the soil particles dissolves, and the particles are in a sub free and loose state. Therefore, the principal stress difference of saturated loess is always smaller than that of undisturbed loess and remodeled loess during the shear process, indicating that saturated water damages the soil structure more than disturbance.

3.4 The variation pattern of structural parameters

3.4.1 Variation law of structural parameters of soil samples with different water contents

Triaxial shear tests were conducted on undisturbed soil with 7 different initial water contents (6%, 11%, 16%, 21%, 26%, 31%, 36%) and remodeled saturated soil with the same dry density. According to the same calculation method and process as in the Section 3.2, the structural parameters of loess samples with different water contents were obtained, and the variation curves of structural parameter with water content are shown in Figure 8.

It can be seen from Figure 8 that under the condition that the loess samples are same soil source and dry density, the structural parameters generally decrease with the increase of water content as a whole. When the water content is small, the reduction of structural parameters is larger; and the variation range of structural parameters decreases significantly, when the water content increases to close to the saturated water content (36%).

For loess, the soil has formed a structure of porous and vertical joints, due to the long-term physical and chemical functions, and cementitious material dominated by carbonate is formed between soil particles. This not only makes the loess have strong structure, but also endows it with special water sensitivity. In loess engineering, water content is generally regarded as a generalized force. Therefore, the effect law of water content on soil structure is basically similar to the influence law of pressure on soil structure. That is to say, the value of structural parameters of loess decreases with the increase of water content. It tends to the minimum when the water content is close to saturation, which is consistent with the experimental results in this paper, as shown in Figure 8. Fundamentally, the reasons for the above phenomenon mainly include two aspects. On the one hand, the cementing substance in loess is mainly soluble carbonate, and the water in the loess dissolves part of the cementing substance between the particles, and the cementation is weakened, that is, the bonding strength between the particles is reduced. With the increase of water content, this weakening effect increases continuously, and the strength of soil samples decreases significantly. On the other hand, the increase of water content thickens the bound water film between soil particles. At this time, the soil samples may change from strong bound water connection to weak bound water connection until free water appears (capillary water or gravitational water) and the connection strength decreases. And the thickening bound water film reduces the friction between soil particles.

When the water content is low, the confining pressure has a great influence on the structural parameters. However, the influence of confining pressure on the structural parameters decreases gradually with the increase of water content. The water sensitivity of soil samples under low confining pressure is stronger than that under high confining pressure. It is mainly reflected in the small variation range of structural parameters with water content under high confining pressure, and it varies greatly under low confining pressure. This is because when the confining pressure increases, the soil samples are compacted, and the water in the soil will be discharged more during the consolidation process, so the high confining pressure has less effect on the soil samples than the low confining pressure.

3.4.2 Variation law of structural parameters under different confining pressures

Plot the structural parameters of soil samples with the same water content under different confining pressure, as shown in Figure 9. It can be seen from the Figure 9 that the structural parameters of soil samples with different water content gradually decrease with the increase of confining pressure. The smaller the water content, the greater the impact of confining pressure on structural parameters. As the water content increases, the amplitude of changes in structural parameters with confining pressure gradually decreases. When the water content increases to saturation, the curve of structural parameters changing with confining pressure approaches a straight line. At low confining pressure, the decrease in structural parameters is significant, indicating that the initial failure rate of the soil sample is very fast; When the confining pressure increases, the decrease in structural parameters greatly decreases.

The reasons for this phenomenon are analyzed in detail as follows. When the confining pressure is small, the confining pressure has a weak densification effect on the initial structure of soil samples, and the soil is relatively loose, so it shows strong structural properties. When increased, the initial structure of soil sample is destroyed during consolidation, that is, the primary structure is damaged rapidly at low strain. In the process of increasing deformation of soil samples in the later stage, the particle arrangement and cementation structure inside the soil mass are constantly adjusted, and the soil sample gradually forms a certain secondary structure under the compaction of high confining pressure. At this time, although the strength of the primary structure is reduced, the healing of the soil structure plays a leading role due to the formation and slow enhancement of the strength of the secondary structure. Therefore, the variation range of the structural parameters of soil samples under large confining pressure and large strain reduced significantly. In the later stage of deformation, the formation of soil secondary structure inhibits the continuous weakening of soil structure caused by structural damage factors, and makes the change of soil structural parameters tend to a stable value in the later stage, which also indicates that the damaged undisturbed loess is gradually forming a secondary structure consistent with the remodeled loess. It can be seen that the structural parameters proposed in this paper under the complex stress state are closely related to the compressive deformation or the strength of the soil.

3.4.3 Variation law of structural parameters under different dry densities

Dry density is one of the factors affecting the structural properties of soil, the increase in density will make the structural variability of loess weakened and its structural stability strengthened, the two together, ultimately leading to structural changes. The values of structural parameters of loess with different initial dry densities were obtained by calculation under the same conditions of soil sample source and moisture content, and the variation curves of structural parameters with dry density are shown in Figure 10.

It can be seen from Figure 10 that the structural parameter m_τ decreases with increasing dry density, while the same source and moisture content of the soil samples. At low confining pressures, the structural parameters vary more with dry density and are more sensitive to dry density; at high confining pressures, the structural parameters vary less with dry density and are less sensitive to dry density. The combined structural potential released by the soil body under loading, immersion, and disturbance is large, and the loss of structural strength corresponds to a large structural parameter. High dry density soils have small voids between the soil particles and the particles are arranged in a relatively stable state. At this time, the soil body is more stable and less variable, so the loess is less structural and corresponds to a small structural parameter. In general, changes in loess dry density affect loess structural variability more than loess stability. Therefore, as the dry density increases, the weakening of structural variability is greater than the strengthening of structural stabilization in the corresponding cases, and the structural properties of loess are correspondingly changed from strong to weak.

4 Discussion

4.1 Stability verification of structural parameters

In order to verify the stability of the structural parameter proposed in this paper, according to the definition of the proposed structural parameter, the relationships between the parameter and the shear strength of the soil samples are first investigated. According to the above description, moisture content is the main influencing factor of structural parameters, so this section focuses on the relationships between structural parameters of soil samples and confining pressure under different water contents. The variation curve of structural parameters with confining pressure is shown in Figure 9.

Multiply the values of each point of the $m_\tau - P$ curve shown in Figure 9 by their corresponding shear strength τ and then make the curve $\tau \cdot m_\tau - P$ of loess samples with different water contents (Figure 11). It can be seen from Figure 11 that the curves of soil samples with different water contents only change within a very small range, which indicates that the structural parameters proposed in this paper are based on the release of comprehensive structural potential. The new definition takes the ratio of shear strength of undisturbed soil and remodeled saturated soil as a structural parameter, it has a good normalization effect on the changes of soil deformation and strength.

The shear strength τ and the structural parameter m_τ of soil samples with different water contents were organized by the corresponding values of shear strength τ at any two pressure levels to produce the m_{p1}/m_{p2}-τ_{o2}/τ_{o1} relationship, i.e., the curve of the ratio of the structural parameter to the inverse ratio of the shear strength (double-ratio curve), shown in Figure 12. It can be seen from Figure 12 that all the data are distributed in a narrow band, the fitting of which shows that the pattern of change of the data has an exponential relationship.

This relationship, which fully demonstrates that the structural parameter m_τ of soil under complex stress state proposed in this paper is well stabilized for soil samples with different water contents, further shows that the water content of soil has a very important influence on the structural properties of soil.

4.2 Rationality verification of structural parameters

This article presents the structural parameters of loess under complex stress conditions. In order to verify the rationality of this parameter, triaxial shear tests were conducted on undisturbed loess with different water contents. The structural parameters of loess samples with different water contents were obtained by calculation.

Table 11 indicates the peak strength, cohesion, internal friction angle and structural parameters of soil samples with different water contents obtained by triaxial shear test, Figure 13 shows the variation trend of various parameters with water content. According to Figure 13, the rationality of the structural parameter is explained in the following aspects.

(1) As the moisture content of the sample increases, both cohesion and the angle of internal friction exhibit a simultaneous decrease. According to the definition of structural parameters, soils with greater structural integrity necessitate higher strength in undisturbed samples while exhibiting lower strength in reconstructed saturated samples. Consequently, when the strength value of the reconstructed saturated sample is established, a stronger original sample correlates with enhanced structural parameters. As the initial moisture content of the undisturbed sample progressively rises, there is a corresponding decline in strength indicators and shear strength, leading to a reduction in the structural parameter as well. This observation aligns with the conclusions drawn in Section 3.4.1.

Analysis of Figure 13 shows that when the water content is 6%, the peak strength of the soil sample is the highest, which can reach about 360 kPa, and the structural parameter is 3.52, indicating a strong structure. With the increase of water content, the structural parameters gradually decreased, and the soil sample structure gradually weakened. When the water content increased to 36%, the peak strength decreased to about 180kPa, the structural parameter was 1.93, and the structure was extremely weak. Based on the definition of the structural parameter in this paper, it is theoretically analyzed that when the water content increases, the strength parameter, the peak strength and the structural parameter decrease, it is consistent with the changing trend of the curve in Figure 13. Therefore, the structural parameters suggested in this paper can reasonably describe the structural changes when the soil water content changes.

(2) Since the soil samples in this experiment are all undisturbed loess from the same soil source, the difference in structure is only caused by the change of water content. Therefore, when the external conditions such as confining pressure are identical, the higher the peak strength of the soil sample, the stronger its structure must be. Theoretically, the change trend of structural parameters and peak strength should be basically consistent. It can be seen from Figure 13A that in the range of test water content, the variation curves of peak strength and structural parameters gradually decrease with the increase of water content. In other words, the variation trend of structural parameters with water content is basically consistent with the peak strength, it indicates that structural parameters can describe structural changes well.

(3) From the definition of structural parameters, it can be inferred that their values must exceed 1. As shown in Table 11, when the moisture content of the soil sample is at 6%, the structural parameter measures 3.52. However, as the moisture content increases to 36% (the saturated level), this parameter decreases to 1.93, aligning with the established definition of structural parameters presented in this study. Consequently, this parameter effectively captures changes in the structural characteristics of loess influenced by moisture.

5 Conclusion

(1) Using the ideology of comprehensive structural potential proposed by Ding-yi Xie, the comprehensive structural potential of soil sample can be fully released by applying a load to the remodeled saturated soil. The ratio of the shear strength of the undisturbed soil to the remodeled saturated soil is defined as the structural parameter of the loess under complex stress state. The definition of the parameter comprehensively reflects the particle connection characteristics and particle arrangement characteristics of the soil.

(2) Analyzing the effects of variations in moisture content on soil strength parameters and shear strength revealed that both the internal friction angle and cohesion decrease with increasing moisture content, with the impact on the cohesion being more pronounced than that on internal friction angle. As the moisture content rises, the shear strength of the soil sample progressively diminishes.

(3) Studied the effects and variation patterns of confining pressure, moisture content, and dry density on structural properties. The results indicate that the soil structure weakens with the increase of these three influencing factors, and the structural parameters decrease accordingly. Overall, the structure is most affected by moisture content, followed by confining pressure, and the least affected is dry density.

(4) The stress-strain curve of soil samples lower than the natural moisture content shows a softening type, and the strain curve gradually changes to a weak-hardening type with the increase of moisture content. The higher the moisture content is, the lower the stress peak is, and the difference of principal stress reaching the same stress variable is also smaller and smaller. With the increase of moisture content, the plastic deformation of the soil sample before failure gradually increases, and the strain corresponding to the peak strength also increases. The principal stress difference of saturated loess is always smaller than that of undisturbed loess and remodeled loess, which

indicates that saturated water damages the soil structure more than disturbance.

(5) Verification indicates that the structural parameters of soil under complex stress states proposed in this paper effectively reflect the influence of moisture content and total consolidation pressure on the structure of loess, demonstrating commendable sensitivity, stability, and rationality.

(6) The structural parameter of loess under complex stress conditions, together with particle size, density and humidity, are regarded as the basic physical property indicator of soil. It has great practical value and development potential in engineering applications.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

X-JW: Conceptualization, Data curation, Investigation, Methodology, Writing–original draft, Writing–review and editing. F-ND: Funding acquisition, Methodology, Supervision, Writing–review and editing. J-YL: Data curation, Investigation, Methodology, Writing–original draft.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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