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Research Article

Experimental Investigation into Compressive Behaviour and Preconsolidation Pressure of Structured Loess at Different Moisture Contents

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This paper investigates the influence of the structured property of loess on its compressive behaviour and proposes a new method for determining the preconsolidation pressure of structured loess soil. A series of oedometer tests were carried out on undisturbed and remoulded loess samples prepared at various moisture contents. The effects of moisture content on the structured yield stress, the preconsolidation pressure, and the structural strength were also captured. It was found that the influence of the structured property of loess on the compression behaviour is divergent between undisturbed and remoulded loess samples. The discrepancy before and after structural yielding is more remarkable for the undisturbed soil. The Casagrande method realized through the MATLAB program can effectively eliminate human factors and accurately calculate the corresponding preconsolidation pressure for undisturbed soil. The effects of moisture content on the method for determining the preconsolidation pressure considering the structured property of loess were discussed. The determination method can accurately evaluate the loess consolidation state in loess regions. The influencing rules which the moisture content exerts on the structured yield stress, the preconsolidation pressure, and the structural strength all conform to exponential functions. The study is of great significance to correctly differentiating the foundation consolidation states and calculating the ground settlement in loess regions.

1. Introduction

An accurate determination of the consolidation state of soil is significant for the calculation of foundation settlement and analysis of stability problems [1–4]. Moreover, the project quality, construction period, and cost are also affected by the accuracy of determination of the soil consolidation state [5–8]. Nevertheless, the soil consolidation state falls into three categories, i.e., the overconsolidation state, normal consolidation state, and underconsolidation state, according to the magnitude of the current pressure applied on soil compared to the preconsolidation pressure. Therefore, the core question of determining the consolidation state of the soil layer is to accurately determine the preconsolidation pressure of soil.

Many investigations have been carried out into the determination of soil preconsolidation pressure. As to how to reasonably determine the preconsolidation pressure, many scholars at home and abroad have proposed various methods. These are such as the Casagrande method, Burmister method, Joes method, Mikasa method, "f" method, graphic method, and densitometric method [9, 10]. However, the calculated preconsolidation pressures using these methods are diverse and the structural effect of structured soil has not been well accounted for [11, 12]. The inflection point on the compression curve of soil was defined by Liu

[13] as the critical average pressure, which varied depending on the physical and mechanical properties of the loess and the age of its origin. Gong et al. [14] believed that the pressure corresponding to the inflection point on the compression curve of undisturbed soil can be regarded as the structured yield stress, which should be the sum of the preconsolidation pressure and the structural strength. By performing tests on old and red clays, Wang et al. [15] found that the preconsolidation pressure is related not only to the loading history of the soil but also to the material composition and the structural characteristics of the soil. Shi et al. [16] performed a research on the characteristics of engineering geological environment at Lingdingyang. Chen et al. [17] analyzed the influence of the structure on the compressive properties of compacted loess with different initial moisture contents. Li et al. [18] conducted a study on the soil-water and shear strength characteristics of unsaturated red clay. Li et al. [19] determined the preconsolidation pressure using quick direct shear tests. Jia and Lei [20] studied the anisotropic consolidation properties of Ariake clay in Japan by the constant rate of strain (CRS) consolidation test using vertically and horizontally cut specimens. Wang et al. [21] analyzed the law of stress-strain under different strain rates based on Lanzhou loess compressive tests. Zhang et al. [22] carried out compression-rebound tests and oedometer tests on specimens prepared at different moisture contents. Xu [23] performed an experimental investigation into the one-dimensional disturbed evolution law of Q3 loess. Jiang et al. [24] researched the consolidation and shear properties of seabed soft soil by means of the one-dimensional odometer and conventional triaxial compressive tests.

Unfortunately, none of these methods take into account the structural properties of the soil. Therefore, if these methods were used to determine the preconsolidation pressure of structured soil, the accuracy of the determined preconsolidation pressure may be not satisfactory. As is known to all, most of the geomaterial has some certain structural properties, especially for the loess [25–29]. Due to the fact that the loess has the overhead or inlaid granular structural type which is formed under the special geological condition and in the special natural environment, the structure of the loess is particularly prominent. The preconsolidation pressure refers to the maximum effective stress which the natural soil has ever suffered in history. However, the soil is a special natural product, which has a strong "memorizing" function for its stress history. Its "memorizing" function can reflect or express, in the mechanical properties of the natural soil, the influence exerted by the factors, such as the generating environment, the geological history changes, and external forces. Therefore, proposing a method for determining the preconsolidation pressure of the structural soil is of great theoretical significance for and has far-reaching influence on correctly judging which consolidation state the soil layer belongs to, the settlement calculation, studying the structure of the soil, and constructing the constitutive model.

In order to explore the effects of the structural properties on the compression curves of the undisturbed and remoulded loess soil, a series of oedometer tests were performed on the undisturbed and remoulded loess soil specimens prepared at several moisture moistures. Secondly, according to the analysis of the compression test results, an investigation was made into the structured yield stress of the undisturbed soil, the preconsolidation pressure of the remoulded soil, and the influence of moisture content on the structured yield stress and the preconsolidation pressure. Finally, the determination of the preconsolidation pressure of the structural loess was carried out. The MATLAB program was used to implement the Casagrande method, which determined the preconsolidation pressure and the structured yield stress. On the basis of the reduction method and the concept of eliminating structural strength, the true preconsolidation pressure of the undisturbed loess can be determined with the help of the compression curve of the remoulded soil samples. The influence of moisture content on the preconsolidation pressure, the structured yield pressure, and the structural strength was further analyzed, and the influencing rules were studied.

Table 1: Material parameters of the loess.

Parameter	Magnitude
Specific gravity, G_s	2.71
Natural moisture content, w (%)	22%
Natural density, ρ (g/cm^3)	1.48
Dry density, ρ_d (g/cm^3)	1.20
Liquid limit, w_L (%)	31.30
Plastic limit, w_P (%)	18.90
Optimum moisture content, w_{opt} (%)	27.2
Maximum dry density, ρ_{mdd} (g/cm^3)	1.69

2. Materials and Methods

2.1. Structured Loess Soil. The loess soil used in the tests was taken from a construction site in the suburb of Xi'an city with the overlying soil depth being 4.0–5.0 meters. The soil sample was yellowish-brown in colour and was in the plastic state which corresponds to a liquidity index ranging between 0 and 1. According to the Chinese standard for engineering classification of soil [30], the tested soil samples in this study were categorized as the typical Q3 loess. The physical and mechanical properties of the soil sample are shown in Table 1.

According to the test requirements, five different initial moisture contents, namely, 8%, 16%, 22%, 28%, and 46.5%, were adopted. The undisturbed loess sample with different initial moisture contents was prepared through the air seasoning method and the water dripping method and then was placed in a moisturizing cylinder for more than 24 hours so that the water was evenly distributed in the sample.

When the remoulded loess sample was prepared, the soil generated during the trimming of the undisturbed loess sample was crushed through a sieve of 1 mm in the aperture diameter. The remoulded loess sample was made using the method of stratified sample pressing. The saturated sample was prepared through the air pumping saturation method.

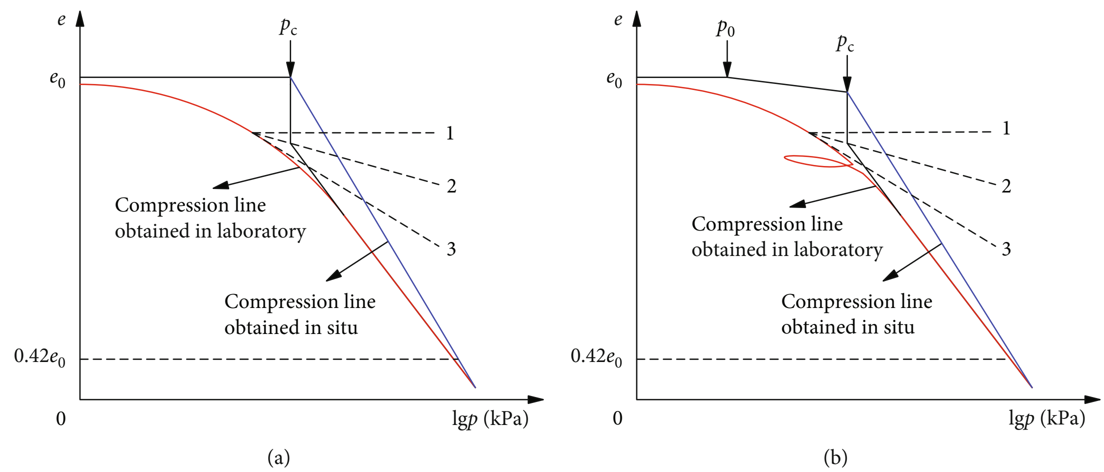


Figure 1: Schematic of compression lines obtained in the laboratory and in situ for (a) normally consolidated soil and (b) overconsolidated soil.

2.2. Oedometer Tests. To explore the effect of the structural properties on the compression curves of the undisturbed and remoulded loess soil and to study the influence of the structural property on the compressive behaviour, different oedometer tests were performed in accordance with the Chinese standard for geotechnical testing method [31]. These oedometer tests are as follows.

(1) The oedometer tests on the undisturbed and remoulded loess soil

(2) The loading-unloading oedometer tests on the undisturbed and remoulded soil samples

(3) The loading-unloading-reloading oedometer tests on the undisturbed and remoulded soil samples with the load being 400 kPa and 800 kPa, respectively

(4) The loading-unloading-reloading oedometer tests on the undisturbed soil samples with the load being 50 kPa, 100 kPa, 400 kPa, and 800 kPa

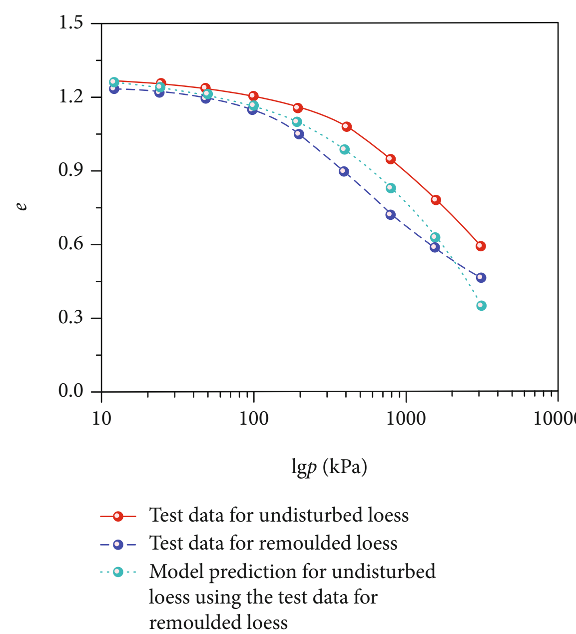


Figure 2: Comparison of the compression lines obtained by tests and model prediction.

3. Preconsolidation Pressure Determination

3.1. Conceptualization and Formulation. The viewpoint proposed by Gong et al. [14] holds the opinion that the corresponding value of the inflection point of the compression curve of the undisturbed soil is the structured yield stress, which is the sum of the preconsolidation pressure and the structural strength, and that the corresponding value of the compression curve of the remoulded soil is the preconsolidation pressure. As is known to all, the traditional Casagrande method has the problem that human factors have great influence on it. The mathematical method which is used to realize the calculating process of this method can eliminate human factors to improve the accuracy of the method. On the basis of the basic theory of the Casagrande method, the MATLAB software was used to realize the Casagrande method, so that the problems caused by the traditional Casagrande method can be eliminated. For example, the maximum value of K can be obtained by the *fminbnd* function of the MATLAB software. Note that K is the minimum radius of curvature for a curve and *fminbnd* is a MATLAB function for finding the local optimized solution for a function. According to the form of the compression curve, the appropriate function can form the fitting curve and then select the appropriate function to solve or program to solve combined with the specific function form, which not only gets rid of human factors but also can carry out reasonable value according to the compression curve of specific soil samples. As to the disturbance caused by the sampling of the soil, Wei [32] had studied the influence of the disturbance on the strength and the compression characteristics of the soil sample. Some scholars have put forward different methods for deducing the preconsolidation pressure, such as on the basis of the concept of the reference state line through three

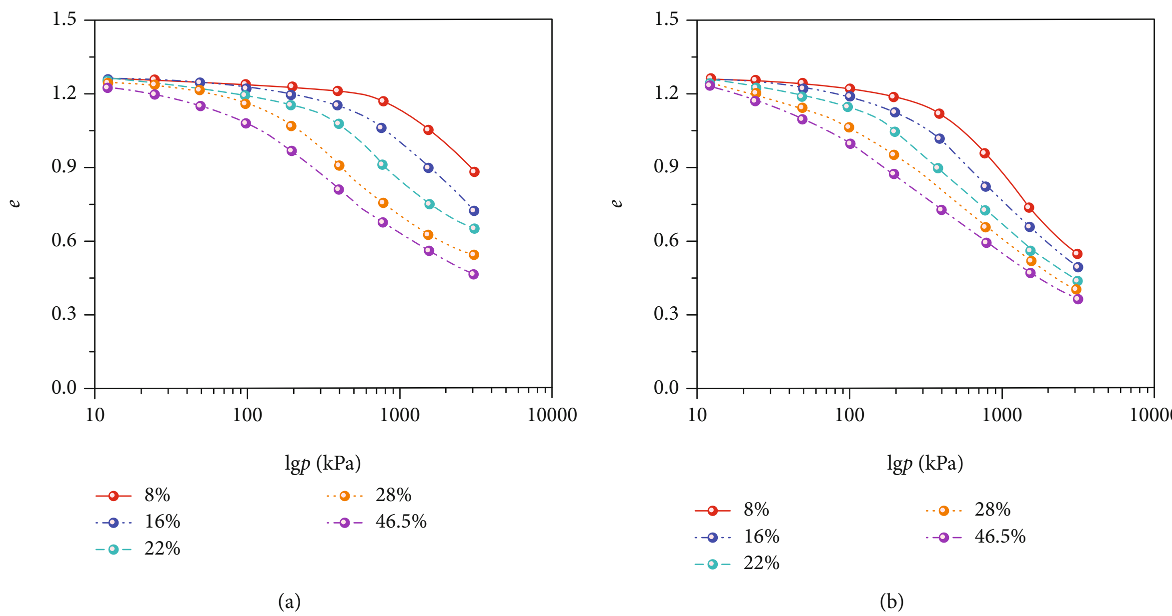


Figure 3: Compression lines at different moisture contents for (a) undisturbed loess and (b) remoulded loess.

corresponding test curves as the reference lines. There are also some domestic scholars, such as Li and Qian [33] who put forward the reduction method, Zou et al. [34] who put forward the iteration method, Wang [35] who put forward the four-stage or three-stage polygonal line analysis method, and Wang et al. [36] who put forward the ameliorating method for the mathematical model proposed by Li and Qian [33]. Umar and Sadrekarimi [37] proposed a method of determining the preconsolidation pressure on the basis of a lot of laboratory tests. Hammam et al. [38] presented the evaluation of preconsolidation pressure of undisturbed saturated clays.

Due to the unloading effect caused by sampling, the laboratory oedometer tests are equivalent to a process of recompression. Therefore, according to the conception of the reduction method and eliminating the structural strength, the real preconsolidation pressure of the structural loess can be determined through reducing the compression curve of the remoulded soil sample. As to this problem, Yang and Wei [39] also pointed out in the analysis of the compression deformation calculation that if the initial pressure which the soil layer bears, namely, the self-weight pressure of the overlying soil layer, falls within the bending section of the curve, the compression index of the straight-line section, must be relatively higher.

As is known to all, from the beginning of the soil sampling to the subsequent preparing and then to the specific tests, every section may have some disturbance of different degrees in the soil, resulting in some changes in its internal structure and stress. In addition, there are the human factors and the factors of test instruments in the process of testing. Therefore, the stress state of the current soil sample is not the stress state of the real in situ soil and it is also called the disturbed soil sample. It is inappropriate and inaccurate to deduce the preconsolidation pressure of the in situ soil by using the results of the oedometer tests at this time to judge which consolidation state the in situ soil belongs to. At the same time, compared with the in situ soil, the sample in the laboratory test truly undergoes a process of unloading and reloading, which is also a disturbance to the original structure of the soil. Generally speaking, the in situ compression curve of the soil and the laboratory compression curve of the soil are shown in Figure 1. In Figure 1, “1” denotes the horizontal line from the inflection point on the compression line, “3” denotes the tangential line at the inflection point, and “2” denotes the angular bisector between “1” and “3.”

In addition, in the process of reduction, the influence exerted by the self-weight unloading of overlying soil and exerted by the recompression should be subtracted and should not pass for the influence exerted by the structural strength. Especially when the soil unloading depth is different, the disparity, which is caused by the self-weight of overlying soil that covers the soil, of this phase between the compression curves of the undisturbed soil sample and the remoulded soil sample will be also enormous, but in fact, it is not caused by the structure.

Particularly for the loess, the confined compression test results indicate that with the changing of the moisture content, the disparity between the compression curves of the undisturbed soil and the remoulded soil increases gradually. To solve this problem, this paper proposes the ameliorating model below:

$$e = e_1 - C_r(\lg p_L)^{1-A}(\lg p)^A + \left(C_c{}' - C_s{}'\right)\lg p_0, \quad (1)$$

$$A = 1 + \frac{\lg(C_s/C_r)}{\lg(\lg p_0/\lg p_L)}, \quad (2)$$

where p_0 is the overburden self-weight pressure, e_1 can be commonly replaced by the initial void ratio of the soil e_0, C_r is the compression index of the remoulded soil, C_s is the

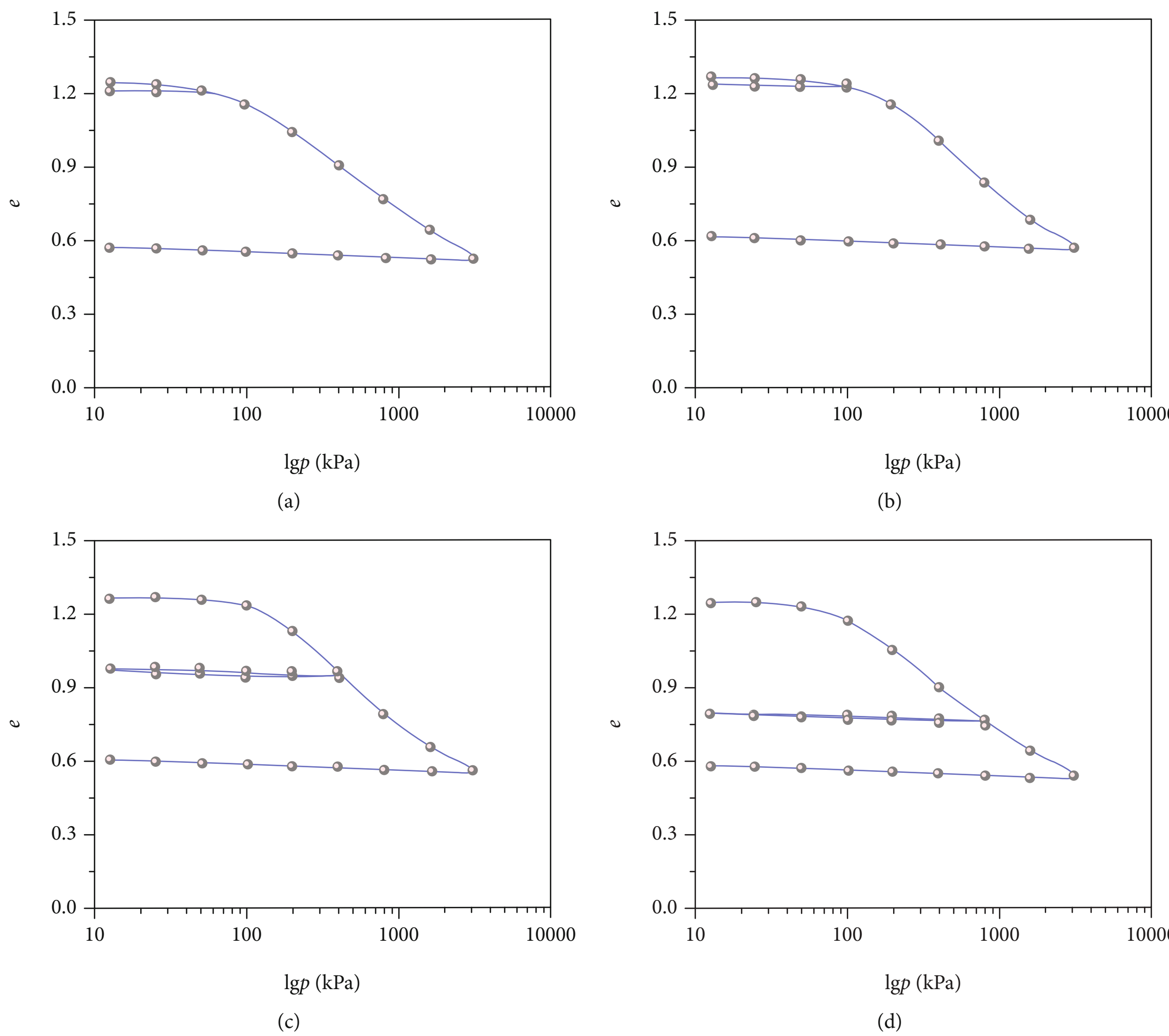


Figure 4: Loading-unloading compression lines for undisturbed loess with the first unloading excursion originating at (a) $p = 50$ kPa, (b) $p = 100$ kPa, (c) $p = 400$ kPa, and (d) $p = 800$ kPa.

unloading index of the remoulded soil, P_L is the corresponding pressure value at the intersection point L, $C_c{}'$ is the compression index corresponding to the overburden self-weight pressure, and $C_s{}'$ is the unloading index corresponding to the overburden self-weight pressure.

3.2. Verification. In this paper, the preconsolidation pressure of the undisturbed loess soil is deduced and calculated on the basis of the compression curve of the remoulded soil sample. The moisture moisture considered in the determination of the preconsolidation pressure is 22%.

According to the test results, the following parameters were derived: the compression index = 0.419, the unloading index = 0.0302, the intersection point $L = 12800$ (which can be obtained by extending the compression curves of the undisturbed soil and the remoulded soil), the initial void ratio of the soil sample = 1.258, and the overburden self-weight pressure = 59.2 kPa. Due to the proportion problem of the test load rate, here, p_0 was taken as 50 kPa, $C_c{}'$ as 0.00343, and $C_s{}'$ as 0.000416. All of the parameters above were substituted into equation (1), which yields

$$e = 1.258 - 0.00623472(\lg p)^{3.9786} + 0.005121. \quad (3)$$

Figure 2 compares the compression lines obtained by tests and model prediction using equation (3). From the comparison, it can be indicated that the determination of the preconsolidation pressure is affected by the sampling process which alters the structural effect of loess. Moreover, it is shown that the compression line of the undisturbed loess can be well predicted by the proposed formulation using the test data for remoulded loess.

4. Results and Discussion

4.1. Test Results. The compression lines at different moisture contents are presented in Figure 3 for the undisturbed and disturbed loess samples. It is found that the compression lines are composed of two stages: the flat stage and the sharp drop stage. The first stage corresponds to a pressure lower than the structured yield stress. At this stage, the soil compressibility is relatively small and the deformation is dominated by the elastic deformation. The second stage corresponds to a pressure greater than the structured yield stress. At this stage, the structural strength, composed of the cementation effect between soil particles and the specific arrangement of soil particles, is incapable of resisting the external load. Therefore, the soil deformation increases greatly because of the internal collapse and the slippage of soil particles. Moreover, the proportion of the plastic deformation in the overall soil deformation is increasing as an increase in the external load.

Figure 3(a) indicates that the influence of moisture content on the compression line is relatively remarkable, especially for the evolution of the two stages. At a relatively low moisture content, the transition from the flat stage to the sharp drop stage is obvious. However, this transition becomes less obvious with an increase in the moisture content. This phenomenon demonstrates that water is the main factor affecting the bonding strength between soil particles and that the structured property of the undisturbed soil has been damaged by water.

From Figure 3(b), it can be indicated that the influence of moisture content on the compression line of remoulded loess soil is relatively small compared to that for the undisturbed loess soil. At a relatively low moisture content (i.e., 8% and 16%), the transition from the flat stage to the sharp drop stage is obvious for the compression line due to the effect of the secondary structure of loess. At other moisture contents, the compression lines are nearly linear without any inflection point. This also indicates that for the remoulded loess soil, the original structured property has been fully damaged by the compaction and sieving during sampling. Furthermore, the effect of moisture content on the compressibility of the remoulded loess soil where soil particles have been rearranged is relatively small.

A comparison of Figures 3(a) and 3(b) indicates that the compressive deformation of undisturbed loess is less than that for remoulded loess at some moisture content and pressure. Therefore, under this pressure, the compression line of undisturbed loess is more gradual than that of remoulded loess. When the loess structure has been fully damaged, the mechanical behaviour of loess is no longer affected by the structured property of loess. In this case, the compression line of undisturbed loess becomes similar to the compression line of remoulded loess. Consequently, a greater moisture content corresponds to a more similar compression line for the undisturbed and remoulded loess.

Figure 4 presents the loading-unloading compression lines for undisturbed loess with the first unloading excursion originating at various pressures. From this figure, it can be indicated that the difference between the slopes of the initial compression line and the unloading-reloading compression line is obvious when the first unloading excursion is originating at 50 kPa. This also demonstrates that the structured property of loess has a significant effect on the shape of compression line before the occurrence of damage to the structured property of loess. For undisturbed loess, when the

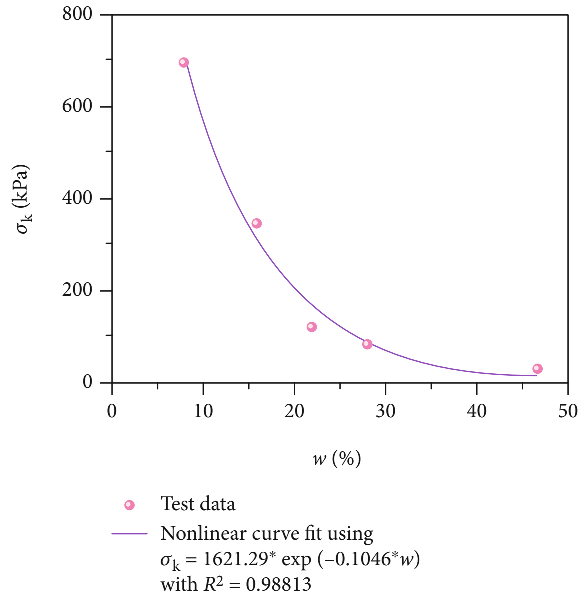
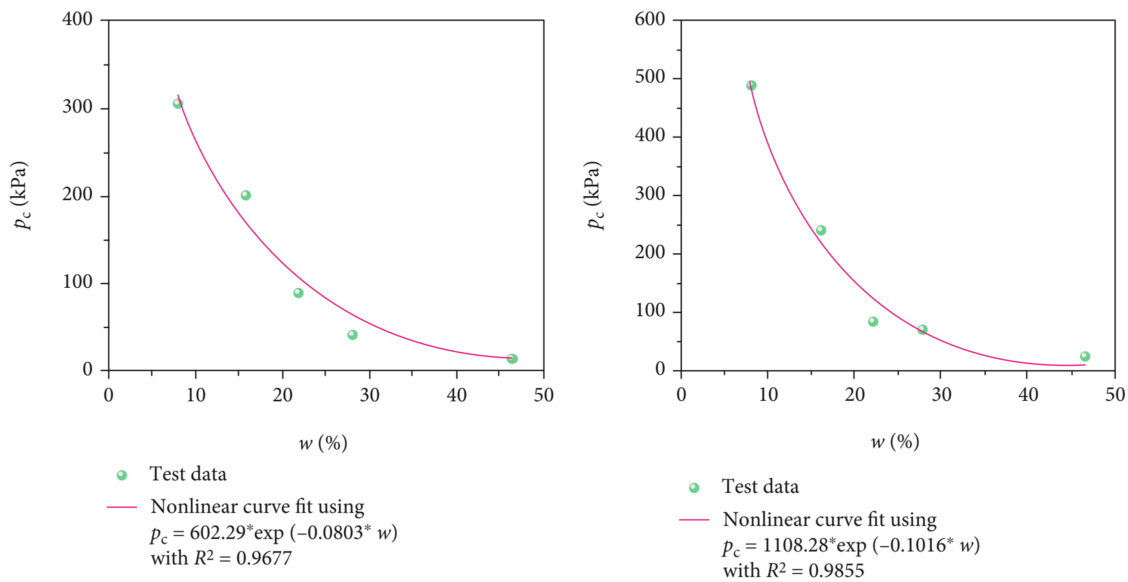


Figure 5: Relation between structural yield stress and moisture content for undisturbed loess.

unloading-reloading occurs at a pressure lower than the structured yield stress, the slope of the reloading line is approximately equal to that of the initial loading line. This means that the swelling index is the same as that of the initial loading line. However, when the pressure becomes greater than the structured yield stress, the slope of the unloading line (i.e., the swelling index) decreases with an increase in the pressure at which the unloading excursion originates, while it increases with an increase in the structured yield stress. This indicates that when the pressure is lower than the structured yield stress, the structured strength of undisturbed loess can resist a certain amount of pressure. In the meantime, the elastic deformation dominates and the plastic deformation is relatively small. Because of this, the swelling index of the unloading line is almost identical to that of the initial loading line. When the pressure is greater than the structured yield stress, with an increase in the pressure, the structured property of loess is gradually damaged by the increased pressure. Finally, the structure of loess is fully damaged, and thus, the slope of the compression line increases while the swelling ability decreases. In other words, the greater the pressure, the less the swelling line.

4.2. Discussion on Effects of Moisture Content. The relation between the moisture content and the structured yield pressure of the undisturbed soil samples is shown in Figure 5 As can be seen in Figure 5, the relationship between the structured yield pressure and moisture content can be well fitted by an exponential function. The function is expressed in equation (4). As can be seen in Figure 5, with an increase in moisture content, the structured yield stress decreases gradually. Nevertheless, the increase in moisture content, when the moisture content is relatively low, obviously has a greater influence on the decreasing extent of the structured



(a)

(b)

Figure 6: Relation between preconsolidation pressure and moisture content for (a) remoulded loess and (b) undisturbed loess.

yield stress than that when the moisture content is relatively high.

$$\sigma_k = a_k \exp\left(b_k w\right). \tag{4}$$

The relation between moisture content and the preconsolidation pressures of remoulded and undisturbed soil samples is presented in Figure 6. As can be seen in Figure 6, the relationship between the preconsolidation pressure of the remoulded soil and undisturbed soil and the moisture content can be expressed by an exponential function as presented in equation (5).

$$p_c = a_c \exp\left(b_c w\right). \tag{5}$$

As to the influence exerted by the moisture moisture on the structural strength, different scholars have obtained different research results, due to the fact that different scholars give diverse definitions for structural strength. For instance, Dang [40] defined the structural strength as the stress difference between the undisturbed loess and the corresponding remoulded loess when the natural structure was destroyed. It was found by him that there was an exponential relationship between the structural strength of the unsaturated loess and the moisture content. Tian et al. [41] made a research and found that the changing curve of the structural strength of the undisturbed loess with the initial degree of saturation of the sample conforms to the relationship of a power function. Xie et al. [42] pointed out that there was the relationship of an exponential function between the structural strength of the Q_2 loess and the moisture content. Chen et al. [43] stated that there was a relationship of the linear correlation between the structural strength and the structured yield pressure.

Based on the tests above, the values of the structural strength of the undisturbed soil under different moisture contents are obtained. The influence which the moisture content exerts on the structural strength is shown in Figure 7. As can be seen in Figure 7, the relationship between the structural strength of the undisturbed soil and the moisture content can be fitted through an exponential function. The expression is expressed in equation (6).

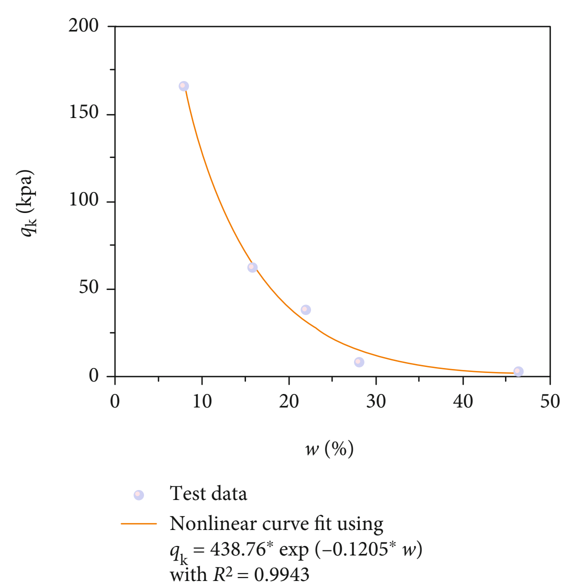


Figure 7: Relation between structural strength and moisture content for undisturbed loess.

$$q_k = a_q \exp\left(b_q w\right). \tag{6}$$

It can be seen from the above that due to the structure of loess formed in the special climatic conditions and geological environment, the microstructure of loess is characterized by macrospores and high strength. However, it contains a lot of mineral components of soluble salts in the loess, which form cementation in the particles. At the same time, due to the different geological history, the particle arrangement shows strong structural strength. However, with the increase of water content, the cementation strength formed by various cementitious substances and water molecules at the contact point of coarse particles is gradually lost and the adsorption cohesion is also partially lost, so the structural strength between particles will rapidly decrease until it is completely lost. The remolded soil sample had adjusted the cementation and arrangement of the particles completely, which does not have the cementation effect on the initial geological environment. In addition, the effect of the arrangement of particles on the whole structure is weaker than that of cementation, so the change of water content has a weaker impact on it. Therefore, the change of water content has an overall impact on the structural strength, structural yield pressure, and preconsolidation pressure of the undisturbed soil sample.

5. Conclusions

Confined oedometer tests were performed on undisturbed and remoulded loess soil samples prepared at different moisture contents to investigate the compressive behaviour of structural loess soil. A method of determining the preconsolidation pressure of structural loess soil was proposed. This method combines the MATLAB-based Casagrande method with the reduction method. Moreover, the influence of moisture content on the preconsolidation pressure of structural loess soil was analyzed. The conclusions drawn from this study can be summarized as follows:

(1) The experimental results indicate that the influence of the structure of loess on the compression curves of undisturbed and remoulded loess soil is significant, especially for the range surrounding the structural yielding point on the compression curve

(2) The proposed method for determining the preconsolidation pressure of structural loess soil is more accurate than the traditional Casagrande method as it considers the structural behaviour and eliminates the personal error

(3) With an increase in the moisture content, the structured yield stress, the preconsolidation pressure, and the structural strength of the loess all decrease gradually, conforming to an exponential function

Data Availability

The data used to support the findings of this study are available from the corresponding authors upon request.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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