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Research Article

Study of Structural and Compression Properties of Soft Soils in Kunming at Different Moisture Contents

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The structure of soil refers to the properties and arrangement of soil particles and pores, as well as their interactions, which have a significant impact on the mechanical behavior of soil. Clarifying the strengths and weaknesses of soil structure can effectively ensure engineering safety during designing. In this study, the structural soft soil in the Wujiaba area of Kunming City was studied. A comprehensive structural parameter γ was proposed by analyzing one-dimensional consolidation test data, which consider both the moisture content and yield stress. Due to its high moisture content and lacustrine features, the soft soil in Kunming possessed obvious structural characteristics. As the moisture content increased, the structural characteristics of the soft soil gradually weakened, making it more prone to compression failure. Moreover, the initial consolidation pressure decreased with the increase in moisture content. And the soft soil was more susceptible to deformation failure with higher moisture content. The conclusions drawn from this study have important implications for predicting the settlement of layered soft soil foundations.

1. Introduction

Soil exhibits structural characteristics in a broad sense [1]. At the microscopic level, these characteristics refer to the properties and arrangement of soil particles and pores, as well as their interactions. Macroscopically, structural characteristics can be described as the mechanical effects of soil structure. When exposed to external forces, the structural characteristics of soil play a crucial role in determining its mechanical behavior, making them a critical parameter for studying soil strength. Structural soft soil is widely distributed worldwide, including the southern coast of South Korea, Mexico City, and other regions. In China, structural soft soil is primarily found in Shanghai, Guangzhou, and Kunming. Structures built on soft soil layers with structural characteristics are highly susceptible to severe settlement deformation, such as buildings, bridges, tunnels, and other constructions. Due to the presence of silty clay layers on the site, the design did not consider the worst geological conditions, combined with heavy rainfall, which resulted in the collapse of a deep foundation pit project in the northwest of Shenzhen in 2018. Furthermore, a collapse occurred at the Nicoll Highway subway station in Singapore in April 2004 because of the rupture of the retaining wall caused by the soft clay layer underlying the excavation when the excavation reached a depth of 34.2 m [2].

Extensive research has been conducted on structure-sensitive soft soil from various angles in recent decades. As such, Li and Shou-yi determined the preconsolidation pressure of soil by studying disturbed soil samples and formulated relevant mathematical equations [3, 4]. Whereas, the general applicability of this formula in structured soil is relatively low. Yu et al. investigated in depth a time-dependent deformation mechanism obtained the viscoelastic-plastic deformation of soft soil using a non-associated flow rule and an improved Nishihara model [5]. However, the complexity of the constitutive model makes it challenging to obtain the parameters, increasing the difficulty of its application in engineering. Jian-qing et al. analyzed the creep characteristics of Dongting Lake's structured soft soil through triaxial tests and established a calculation model that considered the influence of confining pressure and consolidation state [6]. This conclusion is widely used in the low moisture content of the structured soft soils in the region, while its applicability in areas with high moisture content soft soils is mediocre. Currently, most research on structured soft soil focuses on solids, but changes in conditions such as moisture content and vibration can also alter the mechanical properties of soft soil, sometimes exhibiting flow characteristics [7–9]. From a mechanism analysis perspective, there are significant variations in the structure of the soil across different regions, which also result in variations in the mechanical properties of the soil. Structural soft soil in the same region exhibits significant differences in mechanical properties at different moisture contents. The soft soil in Kunming area belongs to lacustrine sedimentary soil and contains multiple layers of peat soil with high organic matter content, low shear strength, high compressibility, poor seismic performance, and a tendency to uneven settlement. Currently, limited research has been conducted on high moisture content areas of structure-sensitive soft soil, which are mostly marine or river sedimentary soft soil [10, 11]. Therefore, conducting research on structure-sensitive soft soil in the Wujiaba area of Kunming is of significant importance.

This paper focuses on studying the soft soil in the Wujiaba area of Kunming and introduces the concept of structural parameter γ, which is obtained through one-dimensional consolidation tests, field measurements, mathematical calculations, and analysis. In particular, compared with traditional formulas, this parameter can intuitively reflect the impact of soil structure on compressibility by analyzing the one-dimensional compression curve. The study analyzes the structural strength and preconsolidation pressure of soft clay with different moisture content from multiple perspectives, providing critical insights for predicting the settlement of structural soft clay buildings and foundations after construction.

2. Experimental Section

2.1. Materials. Located in the middle Yunnan Plateau, Kunming is a typical inland faulted basin, primarily consisting of lacustrine sediments, swamp sediments, and river flat deposits. Soft soil deposits of the Holocene period, predominantly peaty soil, which are distributed mainly from the southern city of Kunming to the north of Dianchi Lake. The study area and soil samples are situated in the western part of Baisha River Road in the Wujiaba area of Kunming City, which is generally flat and open. The soil in this area is structurally soft and widely distributed. Based on geological data from the Kunming region and analogous engineering strata, the drilled soil layers can be classified into 10 major layers and 16 sublayers, primarily consisting of clay, silt, and peaty soil. Peaty soil exists in seven of the exposed geological layers and is widely distributed in the study area in the form of interlayers, or lenticels. It possesses relatively poor engineering mechanical properties.

2.2. Moisture Content Test. The soil used for this experiment was obtained from the interior of the excavation foundation pit. The moisture content of the initial soil was measured using the oven-drying method. Specifically, 15–30 g of representative soil samples were placed in a weighing box, and the wet soil mass was measured. The samples were then dried in a 105°C oven for 8–10 h until the weight stabilized, and the dry soil mass was measured. The moisture content of the soil sample was calculated as the ratio of the difference between the wet and dry soil masses to the dry soil mass.

2.3. One-Dimensional Consolidation Test. To investigate the structural yield characteristics of Kunming soft soil under various moisture contents and loads, indoor one-dimensional consolidation tests were conducted. Five natural moisture content samples (79%, 116%, 118%, 126%, and 169%) were specifically chosen to examine the effect of moisture content on the structural behavior of Kunming soft soil.

The indoor one-dimensional consolidation experiment was conducted in strict accordance with the soil testing method standard (GBT50123-2019) using a conventional consolidation apparatus. The sample had an initial height of 20.0 mm and an inner diameter of 61.8 mm. Prior to sample installation, the inner wall of the consolidation apparatus was coated with silicone oil to reduce friction. To ensure double-side drainage and sample stability, absorbers with a filter paper were placed at both ends of the sample. The test involved loading at increments of 12.5 kPa, 25 kPa, 50 kPa, 100 kPa, 200 kPa, 400 kPa, 800 kPa, 1200 kPa, 1600 kPa, and 3200 kPa, respectively. In addition, a load-unload-reload consolidation test was also performed. In this test, the reloading was carried out step by step according to the loading mode described above until it reached 800 kPa and then unloaded to 100 kPa. After the deformation stabilized, the sample was loaded to 800 kPa at the same rate as the initial loading. The consolidation or rebound stabilization time for each stage of loading or unloading in the test was 24 h.

3. Research Methods and Ideas

Soft soil is generally characterized by a certain structure, high sensitivity, low strength, and low structural strength. After the excavation of foundation pits, perimeter unloading or dynamic loads can reduce the strength of soft soil and increase deformation, which has an adverse effect on the surrounding environment around the pit inversely [12]. To fully investigate the changes in mechanical parameters, such as yield stress, undrained shear strength, compression index, and consolidation coefficient of soft soil in the Kunming area after disturbance, the structural properties of soft soil were analyzed by using the $e - \log p$ curve, the $e - p$ curve, and compression index data. Alternatively, the correlation between the moisture content and the structural properties of soft soil was deduced.

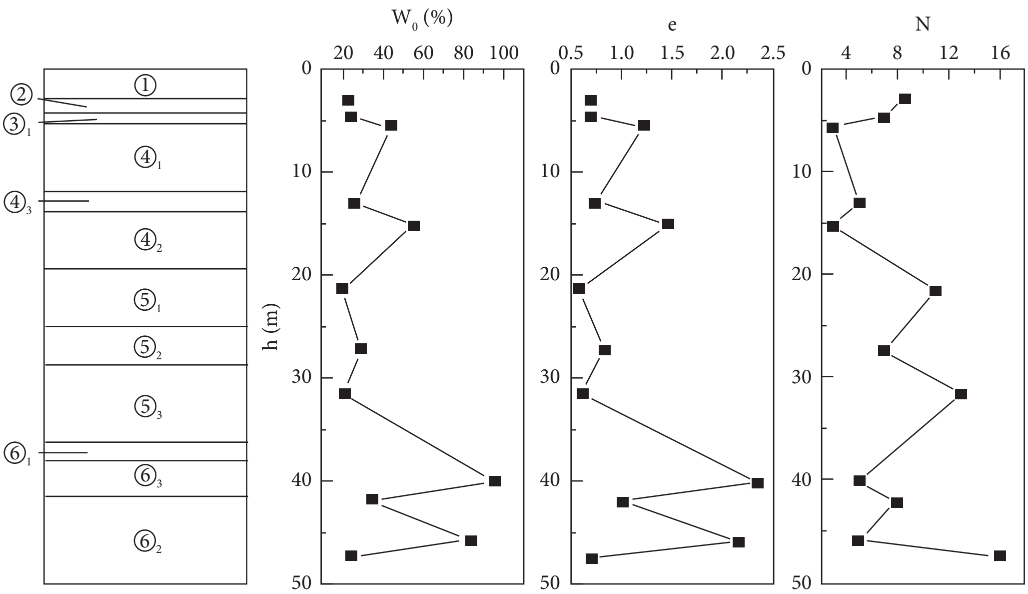

Figure 1: Soil layer distribution and main physical and mechanical parameters of the site.

3.1. Compression Deformation Analysis of Soft Soil in the Study Area. After studying the structural soft soil samples, it was discovered that the physical and mechanical characteristics of the soil layers significantly differed based on their moisture content. Among them, the moisture content of peaty soil layers ranges from 75% to 180%, with a natural porosity ratio of over 2 and a standard penetration number of less than 6. Although the compressive strength is low, the organic matter content is around 30%. And the bearing capacity is poor. The structural response of peaty soils to vibration is distinct from that of clay and silt (as shown in Figure 1). This study exclusively focuses on the analysis of peat-like soil samples with distinctive properties in the stratum.

The compression $p-s$ curves and $e-\log p$ curves were obtained through a one-dimensional consolidation test on soil samples with varying moisture content (Figure 2). It is evident that the compression response of soil remains consistent across different moisture contents, and the trend of soil deformation is consistent as well. With the increase in vertical pressure, the deformation gradually increases. The $p-s$ curve (Figure 2(b)) indicates that the sample with 169% moisture content undergoes a deformation of approximately 10 mm at the same stress level. The $e-\log p$ curve (Figure 2(c)) exhibits a clear inflection point for soft soil with large pore spaces, corroborating the characteristics of overconsolidated soil. When the vertical stress is less than the corresponding value at the inflection point, the soil undergoes predominantly elastic deformation. But beyond this point, the unrecoverable plastic deformation of the soil increases sharply, which is manifested by a significant reduction in strength and a greater compressibility and yielding of the soil. Moreover, the $e-\log p$ curve reveals an early appearance of the inflection point with increasing moisture content. The inflection point pressure value of the 169% soil sample is approximately 200 kPa, while that of the 79% soil sample is as high as 880 kPa. These results indicate that high moisture content induces lower yielding load-bearing capacity in the soft soil structure. Furthermore, the load causing the structural failure of soil and its yielding force are negatively correlated with the moisture content. After the load exceeds the yield stress, the $e-\log p$ curve of different moisture content soil samples closely approximates a straight line, and the slope of the straight line is the compression index C_c of the undisturbed soil. The pore ratio at the inflection point represents the yield pore ratio e_y.

Observations derived from Figure 2(d) indicate that, at the same vertical pressure levels, an increase in the moisture content of soil samples leads to a reduction in compression modulus, while the strength and stiffness of the soft soil with lower moisture content are greater. The vertical pressure curve exhibits a negligible attenuation process up to 2000 kPa, primarily attributable to the resilient structural properties of soft soil. Initially, the soil's inherent structural components oppose external forces, and upon exceeding yield stress, the pores get compressed, causing a steady escalation in compression modulus with increasing pressure. This phenomenon is consistent with Li et al.'s observations, indicating that the soft soil in Kunming belongs to the category of high-moisture-content structured soft soil [13].

Drawing upon the findings of the aforementioned experimental outcomes and the distinct properties of soft soil prevalent, this paper establishes the moisture content-compression index correlation as a key indicator for evaluating soil structural integrity. Figure 3 illustrates the resultant curve and fitting equation $C_c = 2.91 - 0.045e + 2.37\times10^{-4}e^2$ ($R^2 = 0.99$). A higher compression index signifies greater compressibility and enhanced deformation capacity of the soft soil. The data presented in Figure 3 confirm that C_c values are 2.03 and 0.831 at moisture contents of 169% and 79%, respectively, thereby lowering the stress threshold for soft soil structural

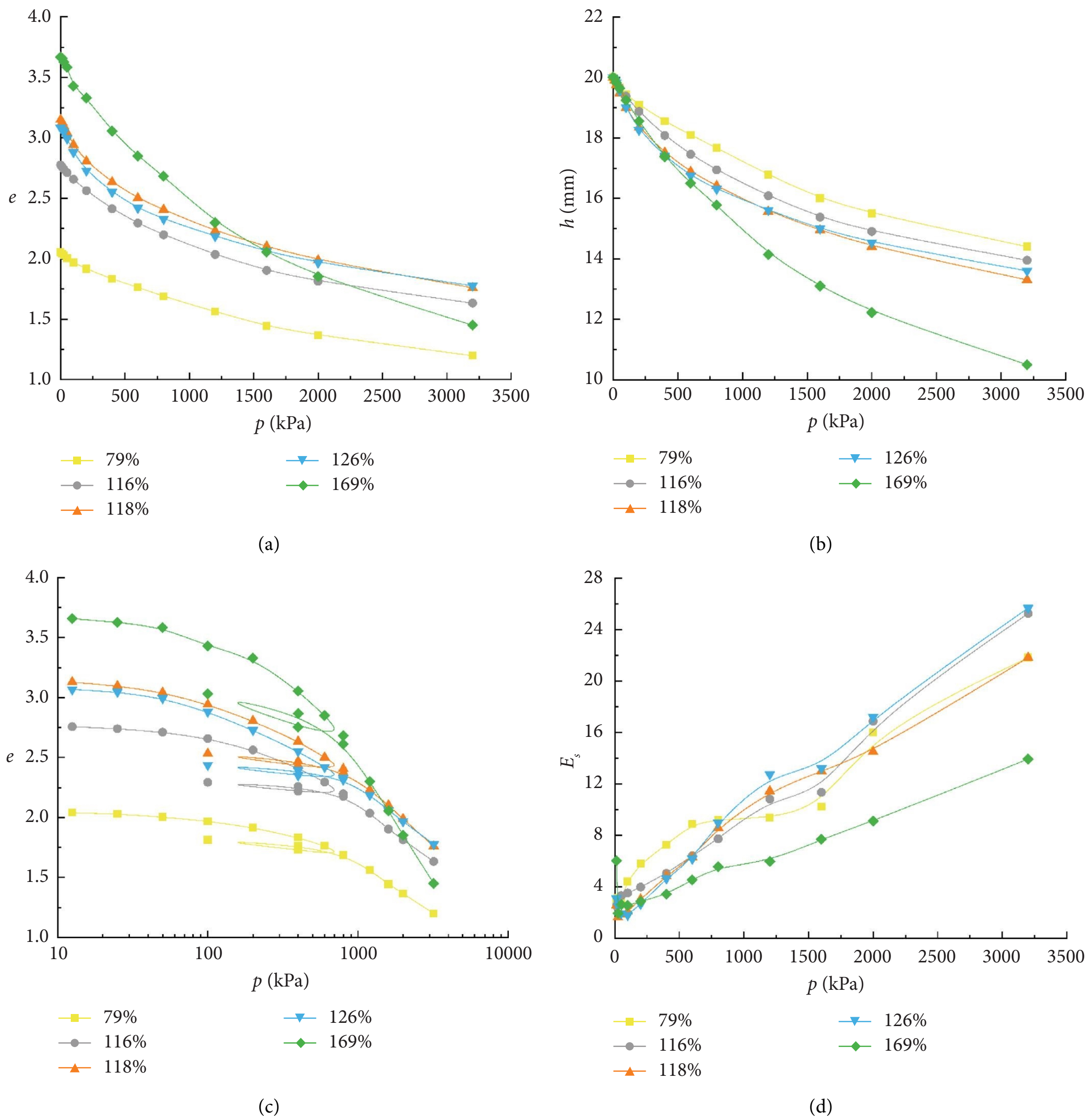

Figure 2: Compression curve of undisturbed soft soil. (a) *e*-*p* curve. (b) *p*-*s* curve. (c) *e*-logp curve. (d) Compression modulus with vertical pressure curve.

yielding. The data also highlight that the structural yield stress decreases with an increase in soil moisture content, and consequently, even small loads can result in compression deformation.

3.2. Structural Parameters. According to the one-dimensional compression $e - \log p$ curves, Liu and Carter et al. studied the difference in porosity corresponding to specific vertical pressure values, and they believed that this difference could reflect the difference between the undisturbed soil and the disturbed soil [14–18]. To further refine the evaluation of soil structural properties, Xie and Qi introduced the concept of integrated structural potential parameters, which allows the concept of structural properties to be better expressed [19]. In a subsequent study, Cun-li et al. verified a correlation between vertical pressure, vertical deformation, and pore ratio, culminating in the development of a structural parameter m_c [20]. Meanwhile, Zai-qiang et al. performed dynamic triaxial tests on relic soils subjected to varied glutinous rice slurry admixtures following dry-wet cycles and obtained the dynamic and structural properties of artificially prepared relic soils [21]. Normalized fitting equations were then formulated to capture the response of soil samples under dry-wet conditions.

In order to comprehensively consider the effects of void ratio and yield stress, this paper introduces the structural index W. Specifically, W is calculated as the definite integral of Δe_1 over the interval $[0, \log p_y]$, denoting the area

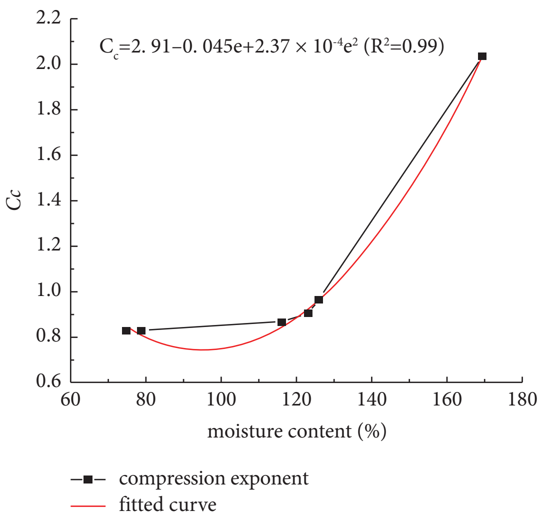

Figure 3: Fitting curve of compression index and moisture content of soft soil.

confined by the $e - \log p$ curve of a given soil sample and its corresponding idealized remodeling curve (see Table 1)

$$W = \int_0^{P_y} \Delta e_0 dp. \tag{1}$$

For structured soils, the region bounded by the compression curve and the hypothetical reshaped curve following reduction is termed as the intrinsic structural index W^*. It is mathematically represented by the integral of Δe_2 over the interval $[0, \log p_y]$

$$W^* = \int_0^{P_y} \Delta e_1 dp. \tag{2}$$

Equation (1) provides a means to derive the structural parameter γ, which is informed by two distinct indices, namely, those depicted in Figure 4

$$\gamma = \frac{W}{W^*}. \tag{3}$$

3.3. Validity Verification. To validate the effectiveness of the proposed structural parameters γ, this study conducted statistical analysis on compression characteristic data collected from prior research. Table 2 presents the structural yield stress, compression index, and structural parameters of representative soft soils. Notably, the statistical data reveal significant variations across samples, with larger structural parameters observed for samples No. 1 and No. 2. The superior structural characteristics of sample No. 1 are attributed to its higher compression index ($C_c = 0.27$), which signifies the soil's greater susceptibility to compression owing to its unstable arrangement of soil particles after yielding and poor cementation. The enhanced structural features of sample No. 2 are attributed to its higher structural yield stress ($\sigma_k = 365$ kPa), implying stronger interparticle cementation and stability. Sample No. 3 retrieved from a soil layer at a depth of 11 m, exhibited relatively low plasticity index and low structural characteristics. Further analysis revealed that the plasticity index of soil is directly proportional to its structural strength, possibly the increased fine particle content, which in turn enhances interparticle forces by expanding soil particle-specific surface areas. Notably, the $e - \log p$ curve of the remolded soil sample No. 4 did not exhibit an evident inflection point. The remolded soil sample formed a "secondary structure," marked by the transition from the overconsolidated state to the normal consolidation state, leading to a significant reduction in structural properties.

The difference in these values indicates that γ can reflect the changes in structural behavior during compression based on the characteristics of the soil sample and comprehensively reflect the variability and stability of soft soil. These data also demonstrate the effectiveness of the parameter.

3.4. Calculation Results and Discussion. The current field sampling methods and various external factors contribute to a certain degree of soil sample disturbance. Strictly speaking, the results of structural soil analysis using field test data may not accurately reflect the actual soil conditions. Li and Shou-yi developed a mathematical model specifically for in-situ samples, yet it remains inadequate for analyzing structural soils [3]. In light of this, Shen proposed replacing the concept of overconsolidation ratio for structural soils with the structural stress ratio ŋ [26]. Furthermore, the prior consolidation pressure calculated by the code should be referred to as the structural yield stress σ. Building upon this, Guo-xin et al. improved the mathematical model by incorporating the structural yield pressure in place of the original overburden pressure P_0 [27]. This modification enables the calculation of the compression curve relationship for in-situ soil, as expressed in the following equation:

$$e = e_0 - C_r (\lg p_L)^{1-A} (lgp)^A, \tag{4}$$

$$A = 1 + \frac{\lg(C_s/C_r)}{\lg(\lg\sigma_k/lgp)}, \tag{5}$$

where e_1 represents the pore ratio at a pressure of 1 kPa, which may be substituted with the initial pore ratio e_0; C_r denotes the compression index of the perfectly reshaped sample, which is defined as the slope of the compression curve of the said sample; C_s is the rebound index of the reshaped sample, which is defined as the slope of the line connecting the end points of the rebound hysteresis circle of the reshaped sample; σ_k signifies the yield pressure of the structure in its original state; and P_L represents the pressure value at the intersection of the compression curve of the reshaped sample and the original sample, which is taken as the pressure value corresponding to the compression curve at $0.59e_0$ according to previously established literature. A represents the reduction coefficient that characterizes the compression curve following reduction.

Utilizing equations (4) and (5), the present study selected data from a soil sample with a moisture content of 169% to demonstrate the principal calculation process and explained

Table 1: Quantitative structural parameters for soft soils.

Scholar (vintage)	Structural parameter	Expression	Experimental conditions	Physical mechanics significance
Xie and Qi [19] (1999)	Synthetic structural potential parameters	$m_p = (s_r \cdot s_s / s_y)$	m_p lateral limit compression	S deformation at the same leve
Cun-li et al. [20] (2006)	Pore ratio structural parameters	$m_p = (e_y^2 \ / e_s \cdot e_r)$	m_p lateral limit compression	e pore ratio at the same level of pressure
Zai-qiang et al. [21] (2022)	Dry-wet cycle structural parameters	$M = (m_1 / m_2) = (\tau_n^2 \ / \tau_s \cdot \tau_0)$	M Dry-wet cycle	τ dry-wet cycle dynamic shear stress

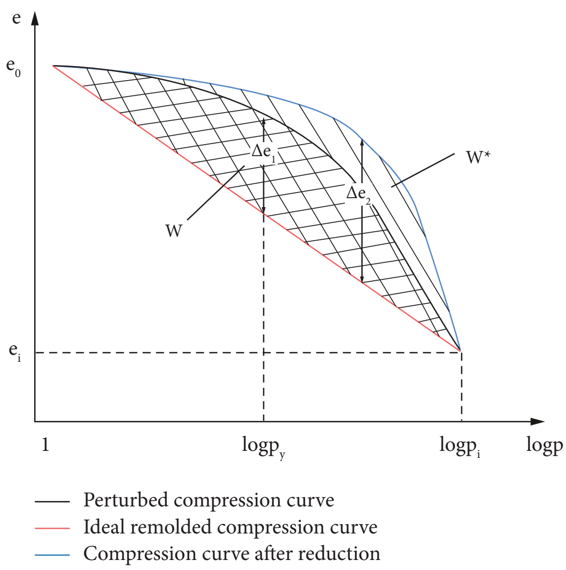

Figure 4: Schematic diagram of structural indices and structural parameters in a one-dimensional compression $e-\log p$ curve.

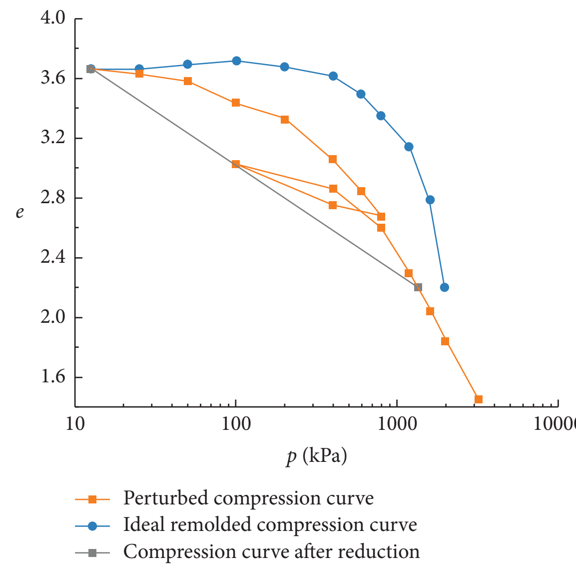

Figure 5: Compression curve after reduction.

Table 2: Statistics of basic parameters of soft soil.

Soil sample	Name	e	(σ_k/kPa)	C_c	γ
1	Leroueil soft soil [22]	2.98	42.83	0.27	0.88
2	Osaka bay soft soil [23]	1.81	365	0.17	0.86
3	Hangzhou Xianghu soft soil [24]	1.8	121	0.8	0.26
4	Artificial structural soft soil [25]	1.2	109.82	0.79	0.41

the main calculation process of the initial consolidation pressure in structural soft soil.

(1) The compression index C_r and rebound index C_s, calculated from the one-dimensional consolidation test compression and rebound curves, were found to be 0.108 and 0.052, respectively. The corresponding pressure $P_L = 1355\,\text{kPa}$ was obtained at the intersection point of ideal remolded soil.

(2) Initial pore ratio $e_0 = 3.658$ and $\sigma_k = 336.6\,\text{kPa}$, the abovementioned calculated values of C_r, C_s, and P_L, were substituted into equation (5) to calculate the reduced compression curve and to derive the calculated equation $e = 3.658 - 0.0028(\log p)^{4.2}$. This equation was plotted to produce a graph, as illustrated in Figure 5.

(3) Using the Casagrande method, the compression curve after reduction was computed, resulting in a prior consolidation pressure value of $P_c = 183.5\,\text{kpa}$.

From equations (4) and (5), as well as the compression curves illustrated in Figure 6, the structural parameter γ corresponding to different moisture contents can be obtained. The results show that as the moisture content increases from 79% to 169%, the value of the structural index W increases continuously, but the normalized structural parameter γ gradually decreases. These results suggest a negative correlation between the structural parameters and the moisture content of soft soil. Considering the relevant definitions of structural parameters, it becomes apparent that as the moisture content of soft soil increases, the yield stress decreases, and that higher levels of moisture content may result in the soil being more susceptible to deformation under relatively low loads.

After fitting the data, a relationship between the structural parameters and the moisture content was established, as illustrated in Figure 7. The equation for this relationship is $\gamma = 2.09 - 0.021e + 6.52 \times 10^{-5} e^2 \,(R^2 = 0.97)$. Since soft soils possess structural properties, their mechanical deformation is significantly influenced by structural yielding damage. Figure 7 demonstrates that the structural parameter is only 0.42 at a moisture content of 169%, and it fluctuates around 0.5 at a moisture content near 120%. The structural parameter of the soft soil decreases exponentially with the increase of moisture content. This trend can be attributed to the elevated internal moisture content of soft soils, which reduces the solidification association between soil particles and weakens the structural properties of the soil.

From the information presented in Figure 6, the prior consolidation pressure values for soft soils with different moisture contents can be calculated using the Casagrande method, as shown in Table 3. These values of P_c provide a clearer insight into the connection between moisture content and yield stress. The correlation is shown in Figure 8 and can be represented by the fitted equation $P_c = 2021.8 - 11.9e - 0.006e^2 \,(R^2 = 0.91)$. It is important to note that P_c is a key parameter in the analysis of soft soil deformation behavior, as it reflects the initial consolidation state of the soil and is an indicator of the soil's bearing capacity.

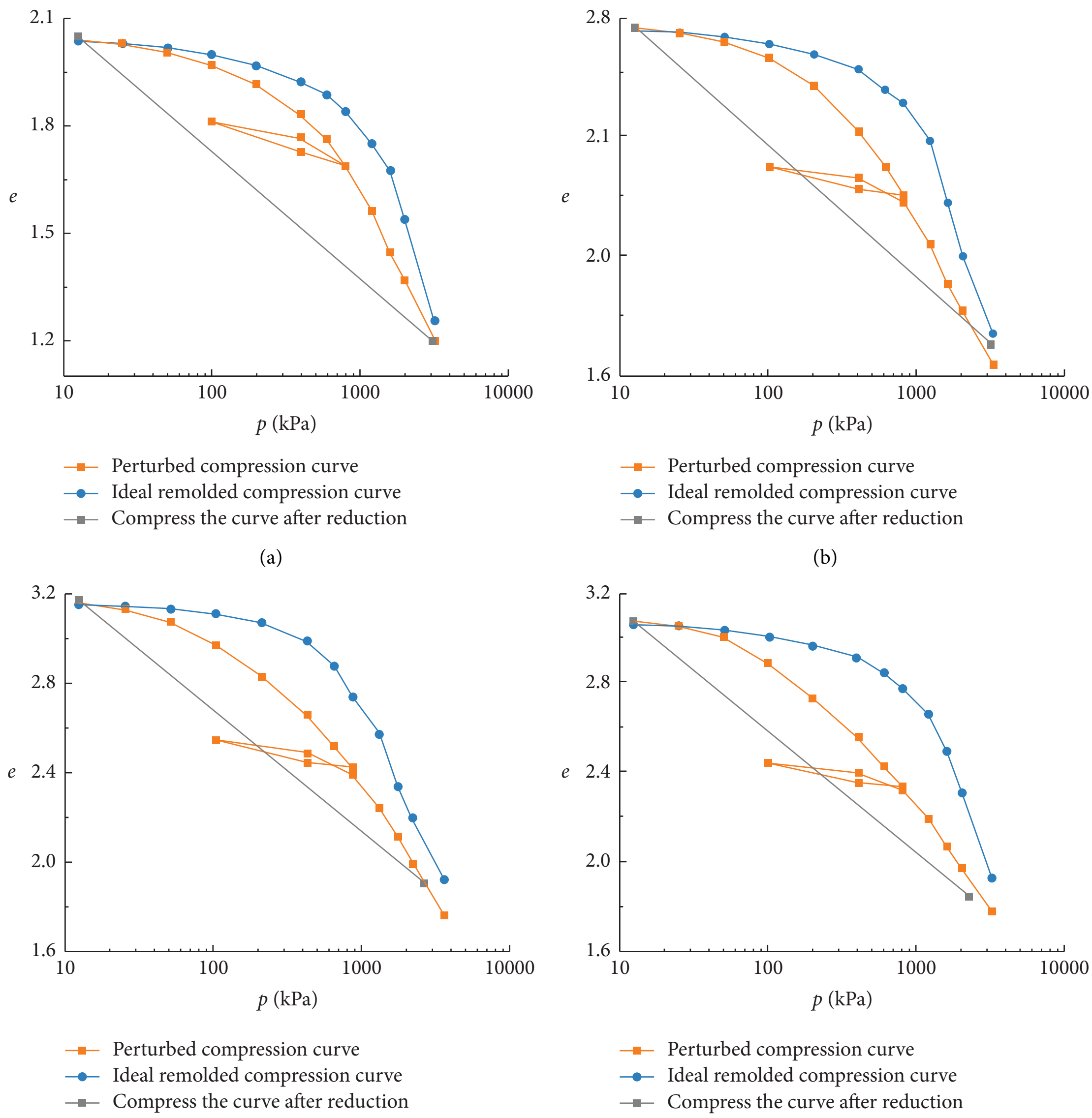

FIGURE 6: Compression curves of soft soil with different moisture contents after reduction. (a) 79%. (b) 116%. (c) 118%. (d) 126%.

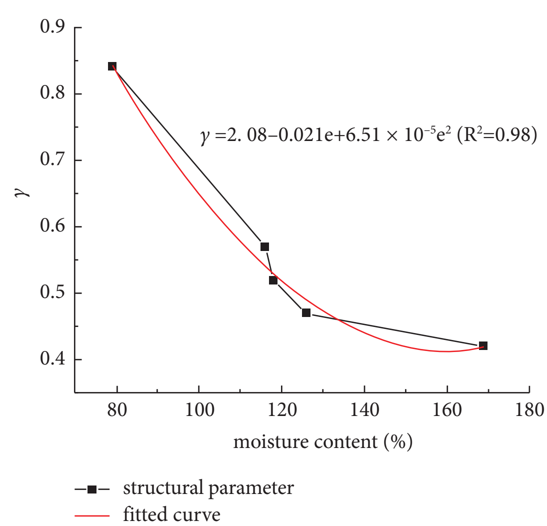

FIGURE 7: Fitting curve of structural parameters and moisture content.

TABLE 3: Prior consolidation pressure values of soft soils with different moisture contents.

Moisture content (%)	79 (%)	116 (%)	118 (%)	126 (%)	169 (%)
P_c (kPa)	1096.7	886.1	653.3	482.6	183.5

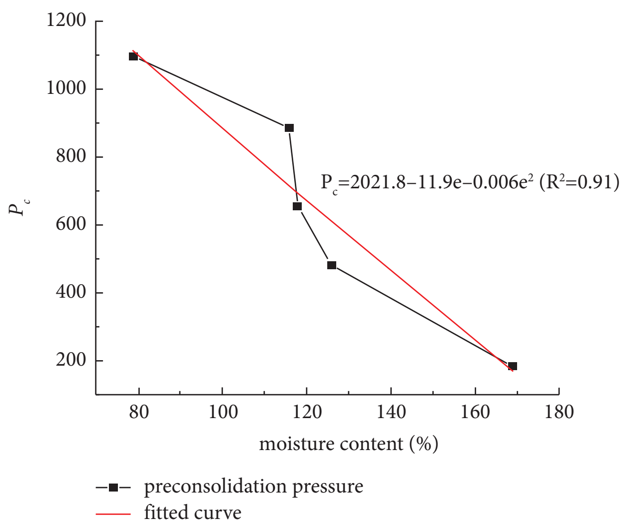

FIGURE 8: Fitting curve of moisture content and yield stress.

The incorporation of structural parameters and the analysis of P_c values discovered the inference that the yield stress of soft soils is inversely proportional to their moisture content. The parameter γ is a direct reflection of the correlation between moisture content and vertical pressure in soft soils. As illustrated in the preceding section, the higher the moisture content, the smaller the value of γ, making the soil more prone to failure under the same load. The formula can be used along with one-dimensional consolidation test data to calculate the value of the structural parameter expressed in void ratio form in any state. In engineering design, the soil's structural strength can be estimated, and its compressive strength predicted by integrating the moisture content and vertical pressure of the area. Hence, when constructing buildings or tunnels in areas with high moisture content, extra caution must be exercised in designing and selecting support methods to prevent potential safety hazards.

4. Conclusion

This paper presents the following conclusions based on the analysis of soft soils with high moisture content in the Wujiaba area of Kunming:

(1) With increasing moisture content, the structural properties of soft soils weaken, resulting in a higher susceptibility to deformation under relatively low loads.

(2) The structural parameter γ can comprehensively consider the effects of void ratio and yield stress. By analyzing the one-dimensional consolidation tests and prior consolidation pressure values, an obvious decay of γ with increasing moisture content was observed in the study area.

(3) Soft soils in Kunming exhibit unique characteristics, such as a high organic matter content of 30% and moisture content ranging from 75% to 180%, and a pore ratio exceeding 2, indicating high structural properties.

(4) The soft soil compression index generally increases with moisture content, while this increase decreases the pressure value corresponding to the yield of the soft soil structure.

In summary, the findings highlight the importance of considering the structural properties of soft soils when designing and constructing buildings or tunnels in areas with high moisture content.

Data Availability

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

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

Guo Wei conducted the experimental work, performed data analysis, provided theoretical explanations, and drafted the manuscript. Shiguang Xu and Tuo Hong provided valuable feedback and constructive suggestions. Gang Chen conducted a thorough review and made substantial revisions to the technical paper. Shaolei Hao contributed to the linguistic accuracy and fluency of the academic manuscript.

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