Experimental study on secondary consolidation characteristics of Kunming peat soil

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Abstract. A series of conventional consolidation tests and 60 d creep consolidation tests were carried out on undisturbed peat soil samples taken from Kunming for the consolidation and secondary consolidation characteristics. The variation rule and formation mechanism of secondary consolidation parameters were analyzed in detail. Test results show that the e - lg t curves of Kunming peat soil under different consolidation pressures show an inverse S-shape, the ratio of secondary consolidation deformation to total deformation is 32.8%. With the increase of consolidation pressure \( p_c \), the \( C_\alpha \) value of peat soil and general soft clay first increase rapidly to the peak value and then decrease gradually. However, different from general soft clay, the peak value of \( C_\alpha \) value of peat soil is higher which appears at the consolidation pressure of 200kPa (preconsolidation pressure of 67kPa). It is believed that this is related to the high content of organic matter and the abundant micropores in the organic matter. The \( C_\alpha/C_c \) value of Kunming peat soil is 0.052, which conforms to the "\( C_\alpha/C_c \) compression rule". According to the soil classification standard based on the coefficient of secondary compressibility, Kunming peat soil belongs to high secondary compressibility soil.

1. Introduction
Peat soil (including peat soil and peat soil) is a special kind of soft soil formed by the complex biochemical process and the geological action of tens of thousands of years under the condition of low temperature and lack of air. According to statistics, peat soil is distributed in 59 countries and regions around the world, with a total area of more than 4.153 million km². The distribution area of peat soil in China is about 42000 km²[1], which is mainly distributed in Northeast Mountain, Qinghai-Tibet Plateau, North China Plain, Yungui Plateau and South China Coast. From the point of view of geotechnical engineering, due to the special mechanism of soil formation, peat soil contains a lot of organic matter and its loose sponge structure, large specific surface area, and high adsorption, resulting in poor geotechnical properties of peat soils, such as high organic matter content, macropore ratio, low density, high water content, high compressibility, and low shear strength, are often regarded as "problem soils"[2].

Compared with the common soft soil, the physical and mechanical properties of peat soil are
significantly different. The main substance of peat soil is plant residues, and the high content of organic matter is the most significant feature that distinguishes peat soil from ordinary soft clay, with the content of organic matter as high as 80% [3], which also leads to poor geotechnical characteristics of peat soil compared with ordinary soft soil. For example, Landva and La Rochelle [4], through one-dimensional compression tests, point out that the vertical strain of peat soil can reach 50% under 50 kPa vertical load, and the secondary consolidation deformation accounts for the main part. Some scholars have pointed out that the ratio of secondary consolidation coefficient and compression index of peat soil $C_{\alpha}/C_c$ in the range of $0.06 \pm 0.01$[5], which is the largest of all kinds of soil in nature, indicating that mud Carbon soil has remarkable creep characteristics. Many engineering practices show that the settlement of peat foundation after construction is significant due to the next consolidation deformation under long-term load. Therefore, ignoring the problem of secondary consolidation of peat soil will lead to unstable failure of geotechnical engineering structures in construction stage or excessive settlement after construction in service stage.

Based on a project in Kunming area, a series of one-dimensional consolidation tests were carried out on the undisturbed samples of Kunming peat soil. The compression properties of Kunming peat soil were analyzed, and the secondary compression characteristics and mechanism were studied emphatically.

2. Test design and test scheme

2.1. Nature of soil samples
The test soil sample is taken from a project site in Xishan District, Kunming City, Yunnan Province. Within the exposure depth range of sampling point drilling, from top to bottom,
① urban mixed fill (about 3.06 m thick layer), ② Silty clay (about 0.87 m thick), ② Clay (about 2.2 m thick), ③ peat (about 4.72 m thick). The undisturbed samples used in the test come from this layer, and the soil depth is 7–9 m. In order to reduce the disturbance to the original sample, the sample was drilled with a thin-walled sampler.

Physical property indexes of soil samples were measured through laboratory tests, as shown in Table 1.

Table 1 Physical and mechanical parameters of peat soils

| Depth (m) | Water content (%) | Specific gravity | Natural void ratio | Saturation (%) | Liquid limit | Plastic limit | Liquidity index | Plasticity index | Organic content (%) |
|----------|-------------------|------------------|-------------------|---------------|-------------|--------------|----------------|------------------|---------------------|
| 7–9      | 158.2             | 2.18             | 3.68              | 92.9          | 77.6        | 48.0         | 0.75            | 29.6             | 49.4                |

2.2. Test contents and methods
After vacuum saturation of the sample, the consolidation test was carried out on the WG type single consolidation instrument. Test types are divided into conventional consolidation test and one-dimensional consolidation creep test, the loading sequence is shown in Table 2. There were 4 groups in conventional consolidation test; There were 2 groups of graded loading tests. For specimens under various loads, the deformation rate is less than 0.001 mm/h, and 60 d per group. For the convenience of subsequent presentation, use CG and FJ to represent conventional consolidation test and graded loading test, respectively.

Table 2 Test programs

| Test purpose                  | Test type             | Sample number | Load sequence                                | Total duration/d |
|-------------------------------|-----------------------|---------------|----------------------------------------------|------------------|
| 1. Preconsolidation pressure  | Conventional         | CG-1          | 6.25 kPa → 12.5 kPa → 25 kPa → 50 kPa → 100 kPa | 8                |
| 2. Compression coefficient    | consolidation tests   | CG-2          | 200 kPa → 400 kPa → 800 kPa (1 d per level)  | 8                |
|                               |                       | CG-3          |                                              | 8                |
|                               |                       | CG-4          |                                              | 8                |
Secondary consolidation characteristics

| Graded loading 1D consolidation creep test | FJ-1 | FJ-2 |
|-------------------------------------------|------|------|
| 25kPa→50kPa→100kPa→200kPa→400kPa→800kPa (10 d per level) | 60   | 60   |

3. Analysis of test results

3.1. Preconsolidation pressure

By one-dimensional compression test of 4 groups of peat undisturbed samples, the $e$-$lgp$ curves were obtained, as shown in Figure 1.

It can be seen that the compression curves of peat soil are in inverse S-shape. After calculation, the compression coefficient of four groups of peat $a_{1.2}$ in the range of $5.7$–$8.8$ MPa$^{-1}$, which is much higher than the lower limit of the definition of high compressibility soil ($0.5$ MPa$^{-1}$), so Kunming peat is high compressibility soil.

![Figure 1. $e$-$lgp$ curve of peat](image1)

![Figure 2. ln$(1+e)$-lgp curves of peat](image2)

The $\ln(1+e)$-$lgp$ double logarithmic method proposed by Butterfield[6] used to calculate the preconsolidation pressure in Figure 2. The $\ln(1+e)$-$lgp$ curve can be divided into two intersecting lines, and the consolidation pressure corresponding to the intersection point is the preconsolidation pressure. By solving the fitting equation, the preconsolidation pressures of 4 groups of peat undisturbed samples were calculated to be $69.4$ kPa, $67.8$ kPa, $71.20$ kPa and $60.3$ kPa, respectively. According to the depth of soil and bulk density of soil, the average overburden pressure is about $64$ kPa. The soil layer basically belongs to the normal consolidation state.

3.2. Characteristics of $e$-$lg t$ curve in peat soil

According to the indoor one-dimensional consolidation creep test, the graded loading curves $e$-$lg t$ peat soil are shown in Figure 3.
Figure 3. $e$-$\lg t$ curve of peat

We can see from Figure 3. that the $e$-$\lg t$ compression curves of peat soil are inversely S under the consolidation pressure at all levels in the graded loading. The EOP point and secondary consolidation coefficient $C_\alpha$ are obtained by Casagrande drawing method and marked in the diagram. It can be seen that when the consolidation pressure is 25kpa, the main consolidation completion time is the shortest (about 100 minutes). In the range of 25 ~ 200kPa, with the increase of consolidation pressure, the main consolidation completion time increases gradually. The reason is that peat soil with initial large void ratio, under the progressive load, the pores gradually decrease, and the time of pore water discharge gradually becomes longer. When $p$ is greater than 200kPa, the completion time of main consolidation does not increase or even decreases slightly, which is related to the structural failure of soil.

In addition, by analyzing the percentage of secondary consolidation deformation of peat soil in the total compression deformation under different levels of load, it is found that the consolidation pressure is 25kPa, that is, the secondary consolidation deformation $S_s$ of peat soil accounts for 43.4% of the total compression deformation $S$ under the first loading, and the average value of $S_s/S$ under different levels of pressure is 32.8%.

3.3. The influence of consolidation pressure $p$ on $C_\alpha$ and mechanism analysis

Figure 4. $C_\alpha$ relationship curve with $p$
Figure 4. shows that with the increase of consolidation pressure $p$, $C_\alpha$ of different soft clays increases rapidly at first, and then decreases gradually after reaching the peak value. Compared with other non-organic soft soil or soft soil with low organic content, the $C_\alpha$ value of Kunming peat soil is between 0.04 and 0.12, which is close to the test results of Guiyue[7], and higher than that of other soft soils in the Figure 4. by 0.001~0.03. [8, 9, 10].

It can be seen from the analysis of Figure 4. that although the general law of $C_\alpha$-$p$ relationship of Kunming peat soil is similar to that of conventional undisturbed soft clay, there are differences: except that the peak value of $C_\alpha$ of Kunming peat soil is significantly larger than that of general soft soil, the consolidation pressure corresponding to the peak value of $C_\alpha$ of Kunming peat soil is 200kPa, not $p_c$.

It is concluded that the reason of the difference is related to the compression mechanism of soil. The secondary consolidation deformation of undisturbed soil is determined by the decrease of soil skeleton stiffness caused by structural damage and the increase of soil skeleton stiffness caused by compaction. When the consolidation pressure is less than the preconsolidation pressure, the structural damage is small, so the $C_\alpha$ is increasing, and when the consolidation pressure is greater than the pre-consolidation pressure, the soil structure is destroyed. Soil stiffness increases rapidly and its $C_\alpha$ decreases. Therefore, the preconsolidation pressure of the undisturbed soft clay is the largest when the initial consolidation stress is that of undisturbed soft clay.

Nevertheless, for peat, the consolidation stress corresponding to the peak value of $C_\alpha$ is 200 kPa, which is not the average preconsolidation stress of 67 kPa. Obviously, for peat soil rich in organic matter, the preconsolidation pressure is not the point of stiffness transition of soil skeleton.

The macroscopic mechanical properties of soil are mainly determined by its material composition and microstructure. It is concluded that the material composition and microstructure of peat soil are more complex (sand, silt, clay aggregate, organic colloid and carbonized plant fiber residue) except honeycomb structure and aerial structure [11]. The micropores in organic colloid and clay aggregate are very rich.

At the early stage of loading, there are more large pores in peat soil and plant residues, and the pore water is easy to be discharged. When the consolidation pressure reaches the preconsolidation pressure, the main consolidation is completed quickly. At this time, the structure of peat soil is destroyed and the macropores are basically eliminated. Different from the ordinary undisturbed soft clay, because of the high content of organic matter and micropore in peat soil [11], the soil does not enter the relative compaction state. With the further increase of consolidation pressure and larger than the pre-consolidation pressure, the increase of consolidation pressure leads to the discharge of water in the micropores, the continuous compression of soil, and the soil with the further increase of consolidation pressure, the water discharge rate and volume in the micropore decrease greatly, the soil enters a relatively dense state, and the macroscopic secondary consolidation coefficient decreases. Therefore, the peak value $C_\alpha$ secondary consolidation coefficient of peat soil is not the preconsolidation pressure but the latter 200 kPa, and the peak value is larger than that of ordinary undisturbed soft clay.

3.4. $C_\alpha/C_c$ of peat soil in Kunming
The $C_\alpha/C_c$ consolidation rule unearthed by Mesri in 1974[12], that is, for similar soils, the ratio of secondary consolidation coefficient to compression index of undisturbed soil is $C_\alpha/C_c$ a certain constant. By analyzing the results of this graded loading test and comparing with the test results of several typical non-organic soft soil in China, the $C_\alpha/C_c$ relationship diagram of peat soil and other soft soil can be obtained, as shown in Figure 5.
We can see from Figure 5. that the $C_\alpha/C_c$ value of peat soil in Kunming is 0.052 (correlation coefficient $R^2 = 0.9746$), which accords with the "$C_\alpha/C_c$ compression rule", which is basically consistent with the results of Guiyue [7], and is larger than other typical non-organic soft soil in China [13,14].

### 3.5. Evaluation of secondary compressibility of Peat Soil in Kunming

Mesri(1973)[15], based on the $C_\alpha$ of the secondary consolidation coefficient, the secondary compression coefficient is proposed to divide the secondary compressibility of the soil body $\varepsilon_\alpha$, and it is defined as $\varepsilon_\alpha = C_\alpha / (1 + e)$. According to the formula of secondary compression coefficient proposed by Mesri, the $\varepsilon_\alpha$ of secondary compression coefficient under consolidation pressure at all levels in this one-dimensional consolidation creep test is shown in Table 3.

| Consolidation pressure $p$ | Secondary compression coefficient $\varepsilon_\alpha$% |
|----------------------------|-----------------------------------------------|
| 25kPa                      | 0.97%                                         |
| 50kPa                      | 1.12%                                         |
| 100kPa                     | 2.24%                                         |
| 200kPa                     | 2.48%                                         |
| 400kPa                     | 1.99%                                         |
| 800kPa                     | 1.63%                                         |

Mesri(1973)[15] classified the secondary compressibility of soil according to the secondary compression coefficient of soil. Table 3 shows that the secondary consolidation coefficient $\varepsilon_\alpha$ of Kunming peat is mainly between 0.9%~2.5%. So Kunming peat soil belongs to high consolidation soil.

### 4. Conclusion

Based on the one-dimensional compression test of unmodified peat soil samples from Kunming area, the following conclusions are drawn by comparing them with other typical soft soil samples:

1. In the consolidation tests under graded loading, the $e$-$\lg t$ curves of peat soil all show an inverse $S$ type, and the $S_e/S$ average reaches 32.8%.
2. Similar to the normal undisturbed soft clay, the peak value of $C_\alpha$ in peat soil increases rapidly to the peak value and then decreases gradually with the increase of consolidation pressure $p$. However, the peak value of $C_\alpha$ in peat soil is higher than that in the normal undisturbed soft clay, ranging from 0.04 to 0.12, and the peak value is not in the preconsolidation pressure, but in the later 200kPa. It is believed that this is related to the high content of organic matter in peat soil and the abundant micropores in...
organic matter.

(3) The $C_\alpha/C_c$ value of peat soil in Kunming is 0.052, which accords with the $C_\alpha/C_c$ compression rule and is larger than other typical non-organic soft soil in China. According to the classification standard of soil based on the $\epsilon_\alpha$ of secondary compressibility coefficient, Kunming peat soil belongs to high secondary compressibility soil.

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