Test study on secondary consolidation behavior of soft soil under different loading paths

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Abstract. Based on a series of one-dimensional consolidation tests for undisturbed samples in Guangzhou Nansha, the relationship between secondary consolidation properties and the stress history, load ratios and overload pre-pressure had been researched. The results show that the division of primary and secondary consolidation of soft soil is not only associated with the consolidation pressure, but also with loading ration, soil compression process and soil permeability decreased, etc factors. The main factors to affect the secondary consolidation coefficient are the loading ratio, pre-consolidation pressure, load duration, pre-consolidation pressure pc etc. Cα presents different regularities. For example, the larger the ratio is, the greater the influence of the coefficient of secondary consolidation is; secondary consolidation coefficient has a peak value when consolidation pressure equal to the pre-consolidation pressure;the longer duration of the front load, the smaller secondary consolidation coefficient of the later load. After preloading, the secondary consolidation ratio Cα and compression index Cc is a constant: Cα/Cc≈0.03. The test results indicate that preloading processing is a good way to reduce post-construction settlement: the secondary consolidation coefficient is small when the soil is over-consolidated state, and it can greatly reduce the amount of secondary consolidation deformation.

1. Introduction

Under external force and internal stress, the soil changes in volume and causes the pore water discharge, this consolidation process is called solid consolidation. Generally, soil consolidation is divided into primary consolidation and secondary consolidation. Primary consolidation refers to the process of pore water dissipation. Secondary consolidation is consolidation deformation caused by soil skeleton creep deformation; this is slowly deformation caused by bound water film creep and the soil grain structure rearrangement, under the condition of excess pore water pressure dissipated and stable effective stress. The mechanism of secondary consolidation has not yet formed a unified understanding. Taylor et al (1940) proposed: the secondary consolidation compression of consolidation test is plastic adjustment of the clay structure [2]. Chen Zongji(1958) considered that, there are two main processes that caused by time effect of secondary consolidation deformation: the volume creep is produced by hydrostatic pressure and the retention is due to shear stress; the soil skeleton is hardening under two main processes [3].

In recent decades, the engineering problems caused by soft soil consolidation settlement (subside) become increasingly prominent, more and more attention is paid on the study of secondary consolidation. Many researches on secondary consolidation influence factors were done [4-9]. For example, Bjerrum et al (1972) [4] considered that, the coefficient of secondary consolidation is related
to pre-consolidation pressure \( (pc) \), that is the higher the \( pc \) value, the greater the secondary consolidation effect; Zeng Lingling et al (2011)\(^9\) studied the impact of structural factor to secondary consolidation and obtained empirical model. On the basis of the existing consolidated research results, this paper researched the secondary consolidation characteristics of various loading process and the distribution law of pre-consolidation coefficients.

2. Basic test methods

2.1. The basic physical characteristics of the soil

Experiment undisturbed soil samples was taken from the Nansha Guangzhou. The basic physical properties indicators of soil are showed in Table 1.

The data in Table 1 show that the natural moisture content of the soft soil is big; the void ratio is between 0.87 to 2.00. They indirectly show that the regional soil have large compression characteristics and low strength characteristics. In addition, soil samples pre-consolidation pressure is small, it is about 50 kPa.

| Soil sample number | Moisture content \( w \) (%) | Proportion \( G_s \) | Density \( \rho \) (g cm\(^{-3}\)) | Void ratio \( e \) | Liquid limit index \( I_L \) | Plasticity index \( I_p \) |
|--------------------|-----------------------------|---------------------|-----------------------------|--------------|---------------------|---------------------|
| 1                  | 63.26                       | —                   | 1.73                        | 1.47         | —                   | —                   |
| 2                  | 50.24                       | 2.62                | 1.75                        | 1.25         | 1.43                | 15.7                |
| 3                  | 75.48                       | 2.64                | 1.53                        | 2.00         | 1.08                | 25.3                |
| 4                  | 32.76                       | 2.59                | 1.84                        | 0.87         | 1.05                | 19.1                |
| 5                  | 44.63                       | 2.59                | 1.75                        | 1.14         | 1.05                | 19.1                |

2.2. One-dimensional secondary consolidation test

1. The test program that not consider preloading load

The tests had gone to the low pressure consolidation instrument of WG pattern. The tests used multi-level loading mode on double-sided drainage. The soil samples were 2cm high and 30cm\(^2\) area. Every stage of loading lasted 3 days (except No. 2 soil sample, its loading time was 6, 6, 3, 13 days). The test programs are as follows:

(1) No. 1 soil sample load stage was 12.5, 25, 50, 100, 200, 400 kPa, the loading ratio \( \Delta p / p = 1 \).

(2) No. 2 the soil sample load stage was 12.5, 50, 200, 400, 600 kPa, the loading ratio \( \Delta p / p \geq 1 \), except the last loading ratio was 0.5.

(3) No. 3 the soil sample load stage was 12.5, 50, 75, 100, 150, 200, 300, 400, 600, 700 kPa, the loading ratio \( \Delta p / p \leq 1 \).

2. Pre-loading load Test

To research how the preload effect on the secondary consolidation characteristics of soft soil, they add preload on two kinds of soil sample. Firstly, the experimenters add pre-pressure to the soil samples and continue 210 min; then unloading rebound 24 hour; at last, add loads progressively. No. 4 soil sample pre-pressure was 200 kPa; No. 5 soil sample pre-pressure was 600 kPa. Soil samples loading ratio were 1, each level load continued 1 day. The test programs are as follows:

(1) No. 4 soil sample load stage was 200, 25, 50, 100, 200, 400, 800 kPa, the loading ratio \( \Delta p / p = 1 \).

(2) No. 5 soil sample load stage was 600, 25, 50, 100, 200, 400, 800, 1600 kPa, the loading ratio \( \Delta p / p = 1 \).

3. Secondary consolidation characteristics analysis

3.1. Distinguish boundary between primary and secondary consolidation
According to Terzaghi theory, deformation - time logarithmic curve is a curve in the initial stages, then there will be the inflection point. Therefore, it can use Casagrande mapping method to determine the primary and secondary consolidation demarcation point.

Fig.1 to Fig.3 are e-lgt curves of non-preloading soil samples. Analysis of these experimental curves can be drawn: curves have larger curvature in a low stress level, and they have clear boundary between primary consolidation and secondary consolidation; as cumulative load increases, the boundary is blurring gradually, and the curve approximation became a straight line.

Therefore, the primary and secondary consolidation division influenced by the following three factors:

1. Loading ratio: No.1 soil sample’s (Fig. 1) loading ratio was 1, No.2 soil sample’s (Fig. 2) the first time loading ratio was 3, from figures, loading ratio was big than the boundary of the primary and secondary consolidation is obvious, the line is typical curve that Terzaghi described. It said that loading ratio have a certain impact on the division between primary and secondary consolidation.

2. Soil consolidation: under cumulative loads, generally, the soil is obvious consolidation under load of the first grade 3 and 4, and then adds the load still, the soil compression decreases. So that the deformation of the main consolidation part is also significantly reduced, the soil deformation is mainly generated in the secondary consolidation, e-lgt curve inflection point no longer exists.

3. Soil permeability reduced affects: followed cumulative load, the soil is compacted, and soil permeability is reduced. The dissipation of the pore water becomes more and more slowly as the load increases, thus it made the boundary between primary and secondary consolidation blurring.

Figures 4 and 5 are e-lgt curves of pre-pressure soil samples. As can be seen from figures, when the consolidation pressure is less than the pre-pressure, e-lgt curve is relatively flat, secondary consolidation coefficient is lower; when the consolidation pressure is greater than the pre-pressure, the e-lgt curve’s slope is obvious steepening, secondary consolidation coefficient changes.
3.2. Secondary consolidation coefficient and consolidation pressure relationship

Buisman (1936) considered that, at the stage of secondary consolidation deformation, deformation and time logarithm curves showed a linear relationship, and then put forward a concept of secondary consolidation coefficient. Secondary consolidation coefficient can obtained to e-lgt curve by soil sample:

$$ C_\alpha = -\Delta \epsilon / (\lg t_2 - \lg t_1) $$

In equation, $t_1$ is a time when the primary consolidation to achieve 100%; $t_2$ is the calculation time about secondary consolidation.

3.3. Soil samples non-preloading load

According to e-lgt curves under each consolidation pressure level, it can obtained secondary consolidation coefficient under relevant consolidation pressure. The Fig.7 is the $C_\alpha$-p curves about typical soil samples. The numbers above the curves are the loading ratios for each stage of load.

$C_\alpha$-p curves of three soil samples showed a common law in Fig.6: secondary consolidation coefficient $C_\alpha$ has a peak value when pre-consolidation pressure $p_c$ equal with consolidation pressure $p$. It also shows that the variation of the $C_\alpha$ value is different when the loading ratio is different.

Except the last loading ratio of No.2 soil sample, the loading ratio basically was $\Delta p/p \geq 1$ about No.1 and No.2. The rule of secondary consolidation coefficient $C_\alpha$ followed the change of the the consolidation pressure $p$: $C_\alpha$ as $p$ increases with increasing when $p<p_c$; $C_\alpha$ reaches a peak value when $p=p_c$; when $p>p_c$, $C_\alpha$ reduces a little at first, and then it reaches a stable value. It has a reason to explain that $C_\alpha$ appears first reduces and then decreases as a stable value: when $p<p_c$, the soil consolidation is more and more obvious as $p$ increases and secondary consolidation effect with the obvious, then $C_\alpha$ reaches a peak value. With further increase of $p$, the soil is gradually compacted under the cumulative load, then secondary consolidation deformation also gradually reduce.

No.3 soil sample’s loading ratio is $\Delta p/p \leq 1$ in Fig.7, the rule of $C_\alpha$ vary with $p$: $C_\alpha$ as $p$ increases with increasing when $p<p_c$; $C_\alpha$ reaches a peak value when $p=p_c$; when $p>p_c$, $C_\alpha$ reduces a little at first, then rise again and reaches a stable value. It is different with $C_\alpha$-p curves of No.1 and No.2 soil sample, the main reason is the different of loading ratio. When $C_\alpha$ reaches a peak value, it decreases with loading ratio decreasing. It means small load increments can’t produce significant secondary consolidation. Loading increment increases with increasing consolidation pressure at the same loading ratio, then the soil compression increases significantly, the secondary consolidation tends to be more obvious also, it leading to increases of the secondary consolidation coefficient. Follow the cumulative load, soil compression gradually stabilized and $C_\alpha$ reaches a stable value. So, loading ratio has great effect on secondary consolidation coefficient.
3.4. Soil samples had preloading load

$C_{\alpha}$ -p curves of preloading soil samples is in Fig.7. At pre-pressure loading $pp$, the soil sample variations of the secondary consolidation coefficient are as follows:

1. When the soil in over-consolidated state, $pp$ is the greater, the greater the $C_{\alpha}$ value. With the consolidation pressure increases, the value tends to a smaller stable value.

2. When $p$ is near $pp$ value, the $C_{\alpha}$ value has increased significantly, showing the same variation of the other soil samples which described before.

3. In the same consolidation pressure, the $C_{\alpha}$ value under over-consolidated state is significantly less than the $C_{\alpha}$ value under normal consolidation.

So, when the consolidation pressure is less than the preloading load, the soil is over-consolidated state and secondary consolidation coefficient is very small. It means that preloading can significantly reduce the secondary consolidation deformation. This conclusion provides an effective technology path to reduce post-construction settlement.

3.5. The relationship between secondary consolidation coefficient and compression index under preloading load

As shown in Fig.8, it is a good linear relationship between secondary consolidation coefficient and compression index under preloading load. In Fig.8, $C_{\alpha}/Cc$ were 0.03 and 0.035 and the correlation coefficient is above 0.95. It is also consistent Mesri and Godlewski\cite{5} pointed out that $C_{\alpha}/Cc$ vaule is between 0.025 to 0.10 for the same kind of undisturbed soil.

4. Conclusions

Secondary consolidation characteristics is one of the most important characteristics of the time-dependent deformation characteristics of soft soil, it has many fuzzy recognition. The test results revealed the following status:
The division of primary and secondary consolidation of soft soil is not only related to the consolidation pressure, but also associated with loading ratio, the soil compression process and soil permeability decrease, etc. The primary and secondary consolidation has obvious boundaries when the soil has larger loading ratio; not obvious on the contrary.

The main factors affect to the secondary consolidation coefficient are the loading ratio, the pre-consolidation pressure, the load duration, etc. The larger the ratio is, the greater the influence of the coefficient of secondary consolidation is; secondary consolidation coefficient has a peak value when consolidation pressure same as the pre-consolidation pressure; the longer the duration of the previous load is, the smaller the coefficient of secondary consolidation of the later load is.

Under the cumulative load, no matter the soil sample been preloaded or not, soil samples consolidation coefficient will tend to a certain value if the soil keeps certain duration of load and loading ratio.

Preloading processing is a good way to reduce post-construction settlement: the secondary consolidation coefficient is small when the soil is under over-consolidated state, which can greatly reduce the amount of secondary consolidation deformation; when the load exceeds the pre-pressure, the secondary consolidation coefficient will increase sharply.

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