Analysis and discussion on post-construction settlement of soft soil foundation treatment test section of highway

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Abstract. Combined with the settlement observation data in soft soil foundation test section of highway projects, the final settlement of soft soil foundation by preloading was calculated by using three-point method, Asaoka method and hyperbola method, and the comparative analysis on the final settlement and post-construction settlement of soft soil foundation were conducted by various calculation methods, then the suitability of calculation methods for post-construction settlement of highway soft soil foundation was discussed. And the results are shown as follows: (1) The final settlement results calculated by three-point method and Asaoka method were less than hyperbolic method, due to only considering the primary consolidation settlement for the first two methods; the calculation results of three methods were close to each other when the secondary consolidation settlement was considered, and the secondary consolidation settlement should be considered when the post-construction settlement was calculated by the first two methods. (2) The post-construction settlement and differential settlement of soft soil foundation test section of highway calculated by three methods were all satisfied with the design requirements.

1. Introduction
As an economical and applicable method, the preloading method has been widely used in the large area and deep soft soil foundation treatment in highway project. The settlement observational projects were usually set up inside some typical test sections prior to the construction of soft soil foundation treatment, and then the final settlement and the degree of consolidation for soft soil foundation can be calculated according to some settlement observation data; the analysis on the post-construction settlement was conducted and whether it was within an acceptable range, and then the unloading time and construction time was determined. There are many kinds of calculation method for soft soil foundation settlement. Combined with the measured settlement of soft soil roadbed, the post-construction settlement of highway soft soil foundation was predicted by Zhang[1], Hu[2], Lu[3] using respectively the hyperbolic method, Asaoka method and settlement rate method. On basis of the settlement varying data of soft soil roadbed with time, the settlement development process of highway soft soil foundation was predicted using respectively neural network method and the growth model method by Zha [4], Zhu [5], Zhao[6]. The SFIA method was applied to predict the post-construction settlement of soft soil roadbed by Xue [7], and the calculated results are close to the actual values. In this paper, combined with soft soil foundation treatment test section of highway projects, the final settlement of soft soil foundation by preloading was calculated by using the three-point method, the Asaoka method and hyperbola method, and the comparative analysis on the final settlement and post-construction settlement of soft soil foundation were conducted by various calculation methods, then the suitability of calculation methods for post-construction settlement of highway soft soil foundation was discussed.
2. Engineering Situation of Test Section

Heshun Foshan - Beijiao highway is the length of 100km and the width of 120m, two-way eight routes for the main lanes and two-way six routes for the auxiliary lanes, which is a city transport hub avenue and landscape avenue in Foshan. The marine and alluvial silt and silty clay soil formed soft soil strata in the construction sites, the maximum thickness for soft soil strata was 15m. The length of soft soil foundation is about 40 percents of entire highway route. The effect of soft soil foundation treatment will directly affect the project investment and engineering quality of highway project. The study on test section of soft soil foundation treatment of highway projects are carried in the early stage of highway construction. The test section is the length of 500m and the treatment width of 9.0m, and the site has no interference and convenient transportation, where is a very representative for soft soil foundation.

In the test section, the drainage consolidation and surcharge preloading method was used as a main soft soil foundation treatment method. Considering the short duration and a relative rare earthwork for the project, under the correct circumstances of formation conditions and the surrounding environmental conditions, three test unit blocks are drawn from the test section. Which is regarded as a test block for explosive-ramming method, later renamed the surcharge preloading method. The test section was arranged with 44 settlement plates, and the development of the surface settlement in the process of soft soil foundation treatment is determined.

3. Calculation Method of the Final Settlement

Normally, the post-construction settlement of road engineering means the settlement will occur during the use life for 20 years, namely the post-construction settlement is the final settlement $S_e$ minus the settlement $S_i$ has occurred. Which is as follows:

$$S_f = S_e - S_i$$

the final settlement $S_e$ is difficult to calculate by theoretical methods, which is usually obtained according to some measured settlement data. There are a variety of methods to calculate the final settlement, three point method, Asaoka method and the hyperbolic method are usually used to calculate the final settlement. Their principle are as follow:

3.1 Three point method

The settlement $S_1, S_2, S_3$ corresponds to $t_1, t_2, t_3$ moment at the time of maximum constant load were chosen from the relation curve between the settlement and time. and be in conformity with the relation $\Delta t = t_3 - t_2 = t_2 - t_1$. According to the common equation of the degree of consolidation $U_t = 1 - ae^{\beta}$, the final settlement $S_f$ is calculated by the following equation:

$$S_f = S_i(S_2 - S_1) - S_3(S_i - S_2)$$

$$S_f = (S_2 - S_1) - (S_3 - S_1)$$

In Equation (2):

$$\beta = \frac{1}{\Delta t} \ln \frac{S_2 - S_1}{S_3 - S_2}$$

3.2 Asaoka method

Asaoka method is established by one-dimensional vertical drains and consolidation equation, and it is a method to predict the future settlement according to the measured settlement. A consolidation fundamental equation is adopted by the follow equation:

$$\frac{\partial e}{\partial t} = C_v \frac{\partial^2 e}{\partial z^2}$$
The settlement $S(t)$ at $t$ moment is as follows:

$$S(t) = \int_{0}^{H} \varepsilon dz$$

(5)

$$\dot{S}(t) = \int_{0}^{H} \dot{\varepsilon} dz = C_{t} \int_{0}^{H} \varepsilon_{0} dz = C_{t} \{ \varepsilon_{s}(t, z = H) - \varepsilon_{s}(t, z = 0) \}$$

(6)

Under the dead load, Equation (4) is equivalent to Equation (7) as follows:

$$S + a_{1}S' + a_{2}S'' + \cdots + a_{n}S^{(n)} + \cdots = C$$

(7)

Due to the fact that the higher order differential becomes smaller quickly, the accuracy of the first order differential term can be satisfied.

$$S + C_{t} \dot{S} = C$$

(8)

The time $t$ is discretized $t = \Delta t \cdot j$ ($j = 1, 2, 3, \cdots$), the settlement $S_{tj}$ at time $t_{j}$ is obtained by the differential expression as follows:

$$S_{tj} = \beta_{0} + \beta_{1} S_{tj-1}$$

(9)

The relationship between $t_{j}$ and $S_{tj}$ is shown in Figure 1, and $S_{tj}$ is the discretized settlement. A linear relationship between $S_{tj}$ and $S_{tj-1}$ is shown in Equation (9), and The relationship between $S_{tj}$ and $S_{tj-1}$ is shown in Figure 2. In Figure 2, the coefficient $\beta_{0}$ and $\beta_{1}$ can be obtained by connecting data points to be a straight line, and then the final settlement $S_{f}$ can be obtained by the following equation:

$$S_{f} = \beta_{0}/(1 - \beta_{1})$$

(10)

**Figure 1.** The relationship between $t_{j}$ and $S_{tj}$

**Figure 2.** The relationship between $S_{tj}$ and $S_{tj-1}$

### 3.3 hyperbola method

Supposing that the settlement development accords with the hyperbolic law, the settlement $S_{t}$ at any moment $t$ can be expressed as follows:

$$S_{t} = S_{0} + \frac{(t - t_{0})}{a + b(t - t_{0})}$$

(11)

In Equation (11), $t_{0}$ is the time zero of the fitting curve; $S_{0}$ is the settlement corresponding to $t_{0}$; $a$, $b$ as the parameters to be determined. Equation (11) can be converted to the following equation:
\[
\frac{t - t_0}{S_t - S_0} = a + b(t - t_0)
\]  

(12)

The line relationship diagram between \((t - t_0)/(S_t - S_0)\) and \((t - t_0)\) can be drawn from the measured settlement data. \(b\) is the slope of the straight line and \(a\) is the intercept of the straight line. When \(a, b, S_0, t_0\) are substituted into Equation (11), the settlement \(S_t\) at any moment \(t\) can be predicted. When the time \(t \to \infty\), the final settlement \(S_f\) can be obtained as follows:

\[
S_f = S_0 + \frac{1}{b}
\]  

(13)

4. Calculation Results of the Final Settlement

Due to the limitation of soil source and transport condition, the filling construction for preloading soil is conducted by two stages. The filling construction for preloading soil at the first stage is conducted in June 2004, and which is long for the preloading time. When unloading, it not only meets the requirements of post-construction settlement, but also the measured settlement rate is close to zero. The filling construction for preloading soil at the second stage is in June 2005, and the main filling construction areas are six and seven area. Based on some measured settlement data of the settlement plate in the surcharge preloading test section, the final settlement is calculated as listed in Table 1. It can be seen from the results, after the drainage consolidation and surcharge preloading treatment, the post-construction settlement in test section meet the requirements for 150mm and soft soil foundation treatment in test section meet also the design requirements.

| Area number | settlement plates number | Measured settlement (mm) | Calculation value for the final settlement (mm) | Area number | settlement plates number | Measured settlement (mm) | Calculation value for the final settlement (mm) |
|-------------|--------------------------|--------------------------|-----------------------------------------------|-------------|--------------------------|--------------------------|-----------------------------------------------|
|             |                          | Asaoka method            | Three point method                           |             |                          | Asaoka method            | Three point method                           |
|             |                          | Hyperbola method         |                                               |             |                          | Hyperbola method         |                                               |
| 1           | T1-1                     | 598                      | 600                                           | T6-2        | 389                      | 387                      | 391                                           |
|             | T1-2                     | 564                      | 562                                           | T6-3        | 295                      | 293                      | 296                                           |
|             | T1-3                     | 360                      | 361                                           | T6-5        | 365                      | 361                      | 366                                           |
|             | T1-4                     | 548                      | 552                                           | T7-4        | 381                      | 383                      | 385                                           |
|             | T1-5                     | 468                      | 467                                           | T7-2        | 346                      | 344                      | 346                                           |
|             | T2-1                     | 599                      | 598                                           | T7-3        | 282                      | 279                      | 286                                           |
|             | T2-2                     | 407                      | 405                                           | T7-5        | 395                      | 392                      | 397                                           |
|             | T2-3                     | 499                      | 501                                           | T7-6        | 260                      | 256                      | 262                                           |
| 2           | T2-4                     | 557                      | 555                                           | T8-1        | 205                      | 206                      | 206                                           |
|             | T2-5                     | 380                      | 377                                           | T8-2        | 296                      | 294                      | 298                                           |
|             | T4-1                     | 576                      | 576                                           | T8-3        | 238                      | 238                      | 238                                           |
|             | T4-2                     | 549                      | 554                                           | T8-4        | 335                      | 334                      | 338                                           |
|             | T4-3                     | 391                      | 391                                           | T8-5        | 300                      | 299                      | 301                                           |
|             | T4-4                     | 523                      | 529                                           | T8-6        | 344                      | 344                      | 346                                           |
|             | T4-5                     | 497                      | 493                                           | T8-7        | 562                      | 562                      | 563                                           |

5. Analysis and Discussion on the Post-construction

5.1. Comparative Analysis on Settlement Calculation Results

As shown from Table 1, the final settlement \(S_f\) calculated by the hyperbolic method is generally larger than the Asaoka method and three point method, and the results calculated by the latter two method are very close to each other. Hyperbolic method is established on the basis of the similarity between
the settlement curve and the hyperbolic curve. It is proved that there is enough precision through much engineering applications, and the final settlement $S_f$ calculated by the hyperbolic method can not draw a clear distinction both final primary consolidation settlement and secondary consolidation settlement. The final settlement $S_f$ calculated by three-point method and Asaoka method is only the final primary consolidation settlement, real final settlement $S_\infty$ should also include the secondary consolidation settlement as follows:

$$S_\infty = S_c + S_\alpha$$

(14)

In Equation (14), $S_c$ is the final primary settlement calculated by three-point method or Asaoka method; $S_\alpha$ is the secondary consolidation settlement calculated by coefficient of secondary consolidation. If the primary consolidation settlement during using life of 20 years is 15 ~ 40mm The final primary consolidation settlement calculated by three-point method or Asaoka method are slightly larger than hyperbola method. According to the engineering experience, the final primary consolidation settlement is calculated using three point method and Asaoka method, and the secondary consolidation settlement calculated by coefficient of secondary consolidation, and then the final settlement $S_\infty$ is calculated by the Equation (14). The method above is more reasonable.

5.2. Analysis on Post-construction

The post-construction settlement $S_r$ of soft soil foundation includes residual primary consolidation settlement $S_{rc}$ and the secondary consolidation settlement $S_\alpha$. In this paper, the coefficient of secondary consolidation of soft soil is obtained by some physical properties index, considering the road using life as 20 years, the secondary consolidation settlement $S_\alpha$ in different test sections are calculated, and then the post-construction settlement $S_r$ are also calculated. According to the calculation, the secondary consolidation settlement of soft soil foundation for test section during the using life of 20 years is not greater than 50mm after soft soil foundation treatment. When residual primary consolidation settlement $S_{rc}$ calculated by the measured data is less than 100mm, the post-construction settlement can meet the design requirements which is less than 150mm. The calculation results of the post-construction settlement for settlement plates in the test section are shown in Table 2.
Table 2. Calculation results of post-construction settlement for settlement plates in the surcharge

| Area No | Settlement plate No | Measured settlement (mm) | Final settlement (mm) | Post-Construction Settlement (mm) | Degree of consolidation (%) | Area No | Settlement plate No | Measured settlement (mm) | Final settlement (mm) | Post-Construction Settlement (mm) | Degree of consolidation (%) |
|---------|---------------------|--------------------------|-----------------------|---------------------------------|-----------------------------|---------|---------------------|--------------------------|-----------------------|---------------------------------|-----------------------------|
| 1       | T1-1                | 598                      | 629                   | 81                              | 95.1                        | 6       | T6-2                | 389                      | 394                   | 55                              | 98.7                        |
|         | T1-2                | 564                      | 573                   | 59                              | 98.4                        |         | T6-3                | 295                      | 301                   | 56                              | 98.0                        |
|         | T1-3                | 360                      | 376                   | 66                              | 95.7                        |         | T6-5                | 365                      | 371                   | 56                              | 98.4                        |
|         | T1-4                | 548                      | 575                   | 77                              | 95.3                        |         | T7-1                | 381                      | 404                   | 73                              | 94.3                        |
|         | T1-5                | 468                      | 492                   | 74                              | 95.1                        |         | T7-2                | 346                      | 360                   | 64                              | 96.1                        |
| 2       | T2-1                | 599                      | 606                   | 57                              | 98.8                        | 7       | T7-3                | 282                      | 286                   | 54                              | 98.6                        |
|         | T2-2                | 407                      | 416                   | 59                              | 97.8                        |         | T7-5                | 395                      | 401                   | 66                              | 98.5                        |
|         | T2-3                | 499                      | 517                   | 68                              | 96.5                        |         | T7-6                | 260                      | 272                   | 62                              | 95.6                        |
|         | T2-4                | 557                      | 569                   | 62                              | 97.9                        |         | T8-1                | 205                      | 212                   | 57                              | 96.7                        |
|         | T2-5                | 380                      | 394                   | 64                              | 96.4                        |         | T8-2                | 296                      | 302                   | 56                              | 98.0                        |
| 4       | T4-1                | 576                      | 606                   | 80                              | 95.0                        | 8       | T8-3                | 238                      | 245                   | 57                              | 97.1                        |
|         | T4-2                | 549                      | 580                   | 81                              | 94.7                        |         | T8-4                | 335                      | 346                   | 61                              | 96.8                        |
|         | T4-3                | 391                      | 416                   | 75                              | 94.0                        |         | T8-5                | 300                      | 305                   | 55                              | 98.4                        |
|         | T4-4                | 523                      | 564                   | 91                              | 92.7                        |         | T8-6                | 344                      | 352                   | 58                              | 97.7                        |
|         | T4-5                | 497                      | 510                   | 63                              | 97.5                        |         | T8-7                | 562                      | 579                   | 67                              | 97.1                        |

By mid-June 2005, the surcharge preloading test section is fully loaded from seven months to thirteen months, and the post-construction settlement calculated by the measured settlement data can meet the design requirements, it is obvious for preloading effect. Considering 7 boards of settlement plates for post-preloading, the preloading time of constant load is one to two months. The settlement rate calculated by some observation data is small, and the post-construction settlement has basically reached design requirements.

Base on the existing settlement observation data and the post-construction settlement calculation results, the differential settlement analysis on the east-west four sections was conducted. The residual settlement was calculated by hyperbola method. The results show that after the treatment by drainage consolidation and surcharge preloading method, the differential settlement for test section road foundation during the using life can also meet the design requirements, and which is less than two thousandths.

6. Conclusion
Combined with Heshun Foshan - Beijiao highway projects, a typical soft soil foundation test section was selected, based on some settlement observation data, the final settlement of soft soil foundation in preloading test section was calculated by using the three-point method, Asaoka method and hyperbola method, the comparative analysis on the final settlement and post-construction settlement of soft soil foundation were conducted by various calculation methods. And the results are shown as follows: (1)The post-construction settlement and the differential settlement for test section road during the using life of 20 years calculated by three methods can meet the design requirements. (2) The final settlement results calculated by hyperbolic method were slightly greater than three-point method and Asaoka method, and the calculation results for three methods were close to each other when the secondary consolidation settlement was considered for the latter two methods. (3) The final settlement calculated by three-point method and Asaoka method only consider the primary consolidation settlement, and the secondary consolidation settlement should be considered when the post-construction settlement was calculated by three-point method and Asaoka method.
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