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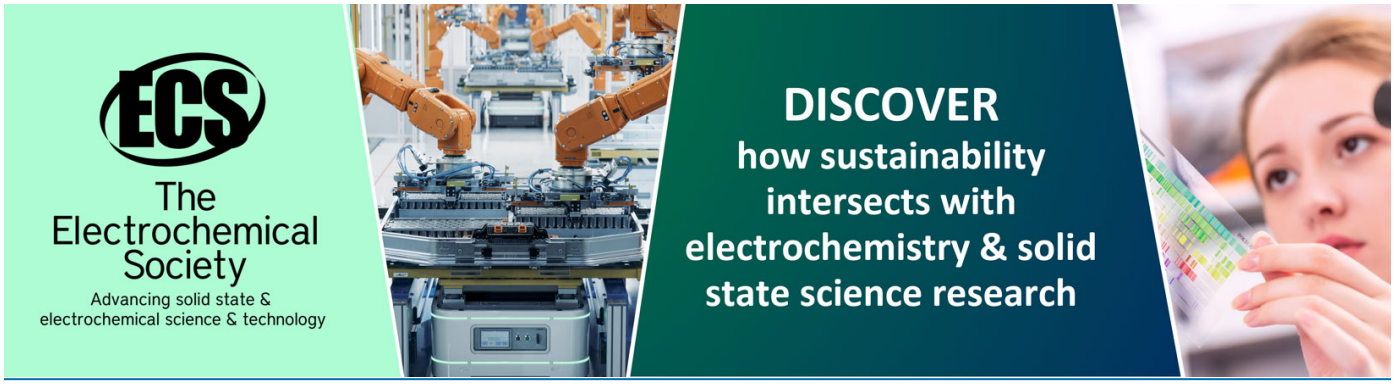

Analysis and discussion on post-construction settlement of soft soil foundation treatment test section of highway

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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_∞ minus the settlement S_t has occurred. Which is as follows:

$$S_r = S_\infty - S_t \tag{1}$$

the final settlement S_∞ 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 $U_t=1-\alpha e^{-\beta t}$, the final settlement S_f is calculated by the following equation:

$$S_f = \frac{S_3(S_2-S_1)-S_2(S_3-S_2)}{(S_2-S_1)-(S_3-S_2)} \tag{2}$$

In Equation (2):

$$\beta = \frac{1}{\Delta t}\ln\frac{S_2-S_1}{S_3-S_2} \tag{3}$$

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:

$$\frac{\partial \varepsilon}{\partial t} = C_v \frac{\partial^2 \varepsilon}{\partial z^2} \tag{4}$$

The settlement $S(t)$ at t moment is as follows:

$$S(t)=\int_0^H \varepsilon \mathrm{d}z \tag{5}$$

$$\dot{S}(t)=\int_0^H \dot{\varepsilon}\mathrm{d}z = C_{\mathrm{v}}\int_0^H \varepsilon_{zz}\mathrm{d}z = C_{\mathrm{v}}\left\{\varepsilon_{\mathrm{z}}(t,z=H)-\varepsilon_{\mathrm{z}}(t,z=0)\right\} \tag{6}$$

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

$$S+a_1S'+a_2S''+\cdots+a_nS^{(n)}+\cdots=C \tag{7}$$

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

$$S+C_1\dot{S}=C \tag{8}$$

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

$$S_{tj}=\beta_0+\beta_1 S_{tj-1} \tag{9}$$

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 $S_{\mathrm{tj-1}}$ is shown in Equation (9), and The relationship between S_{tj} and $S_{\mathrm{tj-1}}$ is shown in Figure 2. In Figure 2, the coefficient β_0 and β_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:

$$S_f=\beta_0/(1-\beta_1) \tag{10}$$

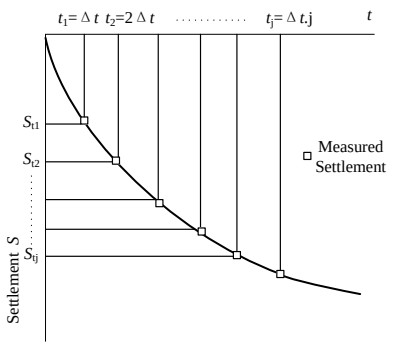

Figure 1. The relationship between t_{j} and S_{tj}

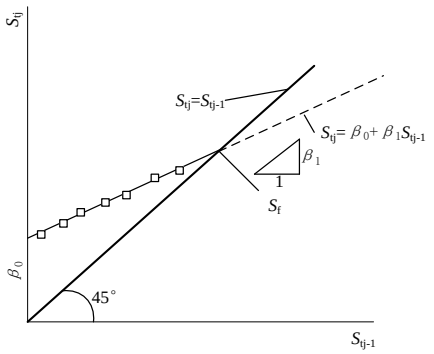

Figure 2. The relationship between S_{tj} and $S_{\mathrm{tj-1}}$

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:

$$S_{\mathrm{t}}=S_0+\frac{(t-t_0)}{a+b(t-t_0)} \tag{11}$$

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:

$$\frac{t-t_0}{S_t-S_0}=a+b(t-t_0) \tag{12}$$

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 $t\rightarrow\infty$, the final settlement S_f can be obtained as follows:

$$S_f=S_0+\frac{1}{b} \tag{13}$$

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.

Table 1. Calculation results for the final settlement in the surcharge preloading test section

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	Hyperbola method				Asaoka method	Three point method	Hyperbola method
1	T1-1	598	600	604	629	6	T6-2	389	387	391	394
	T1-2	564	562	566	573		T6-3	295	293	296	301
	T1-3	360	361	363	376		T6-5	365	361	366	371
	T1-4	548	552	555	575	7	T7-1	381	383	385	404
	T1-5	468	467	471	492		T7-2	346	344	346	360
2	T2-1	599	598	601	606		T7-3	282	279	286	286
	T2-2	407	405	408	416		T7-5	395	392	397	401
	T2-3	499	501	501	517		T7-6	260	256	262	272
	T2-4	557	555	558	569	8	T8-1	205	206	206	212
	T2-5	380	377	381	394		T8-2	296	294	298	302
4	T4-1	576	576	581	606		T8-3	238	238	238	245
	T4-2	549	554	556	580		T8-4	335	334	338	346
	T4-3	391	391	396	416		T8-5	300	299	301	305
	T4-4	523	529	528	564		T8-6	344	344	346	352
	T4-5	497	493	498	510		T8-7	562	562	563	579

5. Analysis and Disscusion 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_∞ should also include the secondary consolidation settlement as follows:

$$S_\infty = S_c + S_\alpha \tag{14}$$

In Equation (14), S_c is the final primary settlement calculated by three-point method or Asaoka method; S_α 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_∞ 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_α. 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_α 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 preloading test section

Area No	Settlement plate No	Measured settlement (mm)	Final settlement (mm)	Post-Construction Settlement (mm)	Degree of consolidation (%)	Area No	Settlement plate Area 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	7	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		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	8	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		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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