Long-Term Settlement Process Prediction for Soft-Clay Pile Foundation Considering Creep Effect

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ABSTRACT

Based on abundant observation data on settlement of soft-clay pile foundation of Beijing-Shanghai high speed railway, the combination prediction model is established by deformation process index method and long-term settlement prediction method, which can consider the loading effect and creep effect. Then the combination model is used to predict the settlement process of 13 typical piers for two super-large bridges of Beijing-Shanghai high speed railway. The fitted curves well approach the actually measured curves, showing that the prediction method is right and practical. In addition, the fitted parameters of settlement curves are statistically analyzed, and the recommended value ranges of these parameters for various soils are provided. The research is practically significant to predict the long-term settlement process of soft-clay pile foundation without monitoring data.

KEYWORDS: Deformation process index method; Soft-clay pile foundation; Long-term settlement prediction; Creep effect; Consolidation settlement

INTRODUCTION

Long-term monitoring results show that[1] the existing buildings have been completed in two to three years or even longer, many buildings settlement still does not stop, some of the buildings settlement needs decades to become stable, it will bring potential safety hazard to building safe use.

Therefore, the design of pile foundation engineering in soft-clay area needs to consider the time effect, which is beneficial to control the foundation stability and it has important significance to improve the building service life.

Engineering experience and analysis show that pile foundation settlement shows certain creep characteristics with the change of time. At the same time, with the construction process, it has a certain stage of development and change process for soft-clay. Therefore, understanding the construction characteristics and the development process for deep soft-clay pile foundation settlement, the final settlement prediction will have a very important significance[2].

From the view of engineering application, the theoretical calculation and numerical simulation of pile foundation settlement have some limitations. It exists some questions of the soil parameters determination and the experimental techniques verification. Through the accumulation of abundant settlement data, based on the statistics analysis to find out pile foundation settlement curves, it can reflect the settlement characteristics and predict the settlement development law. This kind of pile foundation settlement prediction method not only has the enough data support, but also can reflect the intrinsic rule. It has the very strong maneuverability and conforms to the project actual need.

The application of the more common settlement curve prediction methods include the specification hyperbolic[3], index curve method[4], consolidation of log with legitimate (three points method)[5], Asaoka method[6], genetic algorithm[7], grey system GM (1,1) algorithm[8] and deformation process index method[9].

To fit and predict the pile foundation settlement curve in Beijing-Shanghai high speed railway, this paper is based on the analysis of a large number of settlement observation data and statistical induction, the combination prediction model is established by deformation process index method and long-term settlement prediction method, which can consider the loading effect and creep effect. Then the combination model is used to predict the settlement process of 13 typical piers for two super-large bridges. The research is practically significant to predict the long-term settlement process of soft-clay pile foundation without monitoring data.

LONG-TERM SETTLEMENT COMBINATION PREDICTION MODEL

The published research[10-12]shows that the long-term pile foundation settlement is mainly caused by the soil creep deformation, the soil consolidation has little influence on the final pile foundation settlement. With indoor model test, the creep effect of single pile in clay was studied by Edil and Mochtar[13]. The results show that the increase of the pile top settlement is mainly due to the shear creep of pile side soil. At present, the long-term settlement law is studied by long-term monitoring, but it often subject to high cost. Therefore, the long-term settlement prediction and the rational use of the observation data are particularly important. To this end, based on the previous research, this paper puts forward a long-term pile foundation settlement prediction model by considering the soil creep deformation characteristics.

Deformation process index method

Commonly used settlement curve prediction method has the hyperbolic method. It is based on a large number of the settlement observation data accumulation, assuming the settlement curve is a hyperbolic model. On the basis of this, predicting the settlement development. These methods lack continuous settlement deformation assessment in different construction stages, without considering the time effect of pile foundation settlement, the pile foundation deformation is not known during the consolidation process. In order to better grasp the development process of pile foundation actual settlement and avoid the legal problems of common curve fitting. Literature[9] puts forward the "deformation process index method". It is based on a large number of actual observation settlement curves, the prominent load and time factors of pile foundation settlement are considered, the final pile foundation settlement prediction method is studied in the deep soft-clay.

Deformation process index method considers the time effect of the whole pile foundation settlement process. The empirical formula of the settlement S_t and time t is:

$$S_t = S_\infty \frac{N_t}{N_\infty}(1 - e^{-\alpha t}) \quad (1)$$

In the formula, t is time variable. S_t is the settlement in the t moment. S_∞ is the final settlement. It is obtained by theoretical calculation and practical observation. N_t is the cumulative constant load on the pile foundation of the t moment. N_∞ is the ultimate dead load on pile foundation. α is the fitted parameters, it is related to the soil layer characteristics, pile foundation arrangement and construction method.

Long-term settlement prediction model of considering creep deformation

The soft-clay creep characteristics were described by three parameters creep model. The model was put forward by Singh and Mitchell[13]. The formula is:

$$\dot{\varepsilon} = \eta e^{\alpha R}\left(\frac{t_i}{t}\right)^m \quad (2)$$

In the formula, $\dot{\varepsilon}$ is the strain rate at a certain time. The formula of the parameter R is $R = q/q_u$. Three creep parameters are η, α and *m*. The range of *m* value is 0.7~1.0, more than 1 of the situation is very small, which has been confirmed by numerous research results. In addition, the soil consolidation deformation mainly occurred in the bridge construction process and a period of time after the construction completion. With the completion of the soil consolidation, the soil creep deformation becomes the main content of pile foundation settlement. According to the formula (2), it is logarithmic relationship between the long-term pile foundation settlement and time. On the basis of this, WANG Zhong-jin and others considered the creep deformation, the long-term pile foundation settlement prediction model was established [10]:

$$S_t = S_{tc} + B\log\left(\frac{t}{t_c}\right) \quad (3)$$

In the formula, t_c is the time of completing the soil main consolidation under the upper loads action. S_t , S_{tc} is the pile top settlement in the t and t_c moments. *B* is the calculation parameter. According to the formula (3), it is known that the main parameters of influencing the S_t are S_{tc}, t_c and *B*, which are related to the soil mechanical characteristics and pile foundation construction process, and so on. Wang Zhong-jin[10] studied the effect of the main parameters for long-term pile foundation settlement prediction. With the increase of the calculation parameter *B*, the long-term pile foundation settlement increases with the passage of time. At the same time, the influence factors are compared and analyzed, when other parameters are the same, S_{tc} and *B* have a great influence for long-term pile foundation settlement prediction, t_c has a relatively small influence for long-term pile foundation settlement prediction value.

At present, S_{tc} is obtained mainly relying on finite element calculation or standard calculation method, according to the field data acquisition is the most direct way, quite on the S_∞ of the deformation process index method in the formula (1), it mainly refers to the consolidation settlement in the upper loads. t_c is the time to complete the main settlement, it's not a theoretical solution, t_c is obtained on the statistical analysis basis of a large number of engineering test data.

Deformation process index method-Long-term creep prediction model

The deformation process index method is mainly based on the final pile foundation settlement to predict the settlement deformation in different construction stages, the biggest advantage is that the load effect in different construction stages and the time effect under the periodic load are considered. Therefore, it can be divided into stages to predict the pile foundation settlement. The long-term creep prediction model is based on the pile foundation main consolidation settlement, it considers the soil creep characteristics to predict long-term pile foundation settlement. If the two methods are combined, the combination prediction method can be established which will consider the load effect and creep effect, considering the mechanical characteristics and construction characteristics of pile foundation in deep soft-clay will reach the purpose of improving prediction accuracy. At the same time, the fitting parameters α and *B* are studied, the pile foundation consolidation settlement and soil creep characteristics will be judged in different construction stages.

The concrete idea of the combination prediction model is:

(1) The cumulative load at a certain stage after the completion of the pile foundation construction is considered as a stage load(N_t), according to the finite element calculation or standard calculation method, S_∞ will be obtained. Then, according to the formula (1), the main consolidation settlement of the *t* moment will be obtained.

(2) The t_c will be judged preliminary through engineering experience and considering the soil creep characteristics. According to the formula (3), the final settlement S_t of the *t* moment will be obtained.

(3) According to the measured settlement data carry out curve fitting to get the values range of the α and *B*.

(4) According to the above operation process, the S_t of the next stage load will be predicted, research on the variation law of the α and *B*.

(5) According to the corresponding relationship of S_t , α and *B* in different load stages, the neural network method is used to optimize the model parameters to establish a combination prediction method for practical engineering.

Based on the above research ideas, the combination prediction model is established, the formula is:

$$S_t = S_\infty \frac{N_t}{N_\infty}(1 - e^{-\alpha t}) + B\, log\left(\frac{t}{t_c}\right) \quad (4)$$

In the formula, *B* is the fitted parameter, it is mainly related to the soil creep characteristics. The other parameters are the same as the formula (1) and (3).

The biggest characteristic of the combination prediction model is that the soil creep deformation after the primary consolidation settlement is considered. At the same time, the model parameters can be fitted and modified in different construction stages, which is valuable to the engineering application.

ENGINEERING APPLICATION

The combination model is used to predict the settlement process of 13 typical piers for Tianjin super-large bridge and Cangde super-large bridge of Beijing-Shanghai high speed railway. The place is flat and most of the land is cultivated, the main strata from top to bottom are quaternary clay, silty clay, silt, silty sand, fine sand and their interbedded strata, there is a lack of individual soil layers in local area. Most of the sections of the surface and shallow layer of foundation soil are flow plastic, soft plastic, plastic state and no bedrock in the hole depth, it belongs to the typical deep soft-clay layer and soft soil layer, it have some characteristics, such as high natural moisture content, high porosity, low strength, high sensitivity, weak permeability, high compressibility, strong rheological properties, deformation factors. This kind of engineering geological property is bad, the settlement calculation and control are difficult.

Tianjin super-large bridge settlement prediction

The total length of Tianjin super-large bridge is 127.63km and a total of 3563 piers. The soil around the pile is generally silty soil, silty clay and fine sand. The pile end is located in the silty soil and silty clay.

There are 3563 piers with settlement monitoring data. The settlement observation curves were analyzed, 159 effective curves were obtained. The time of erection beam was shifted to the same time point, the total available settlement curves were drew, as shown in Figure 1. This paper will focus on the effective settlement curves, using the combination model to fit and predict the settlement.

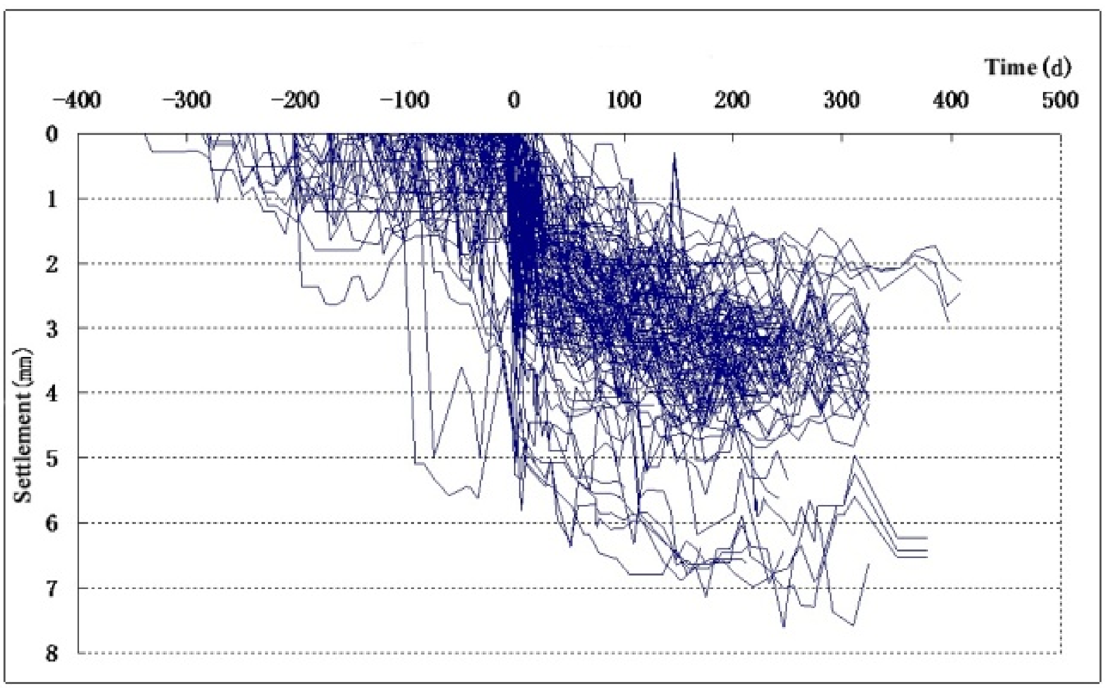

Figure 1: Settlement curves for Tianjin super-large bridge

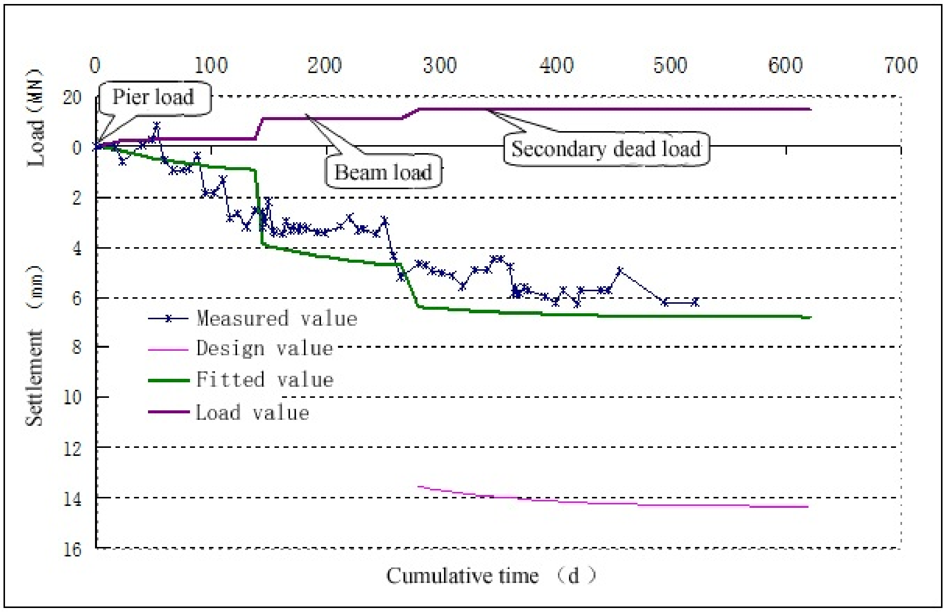

Figure 2: Settlement fitted curves for H109# pier

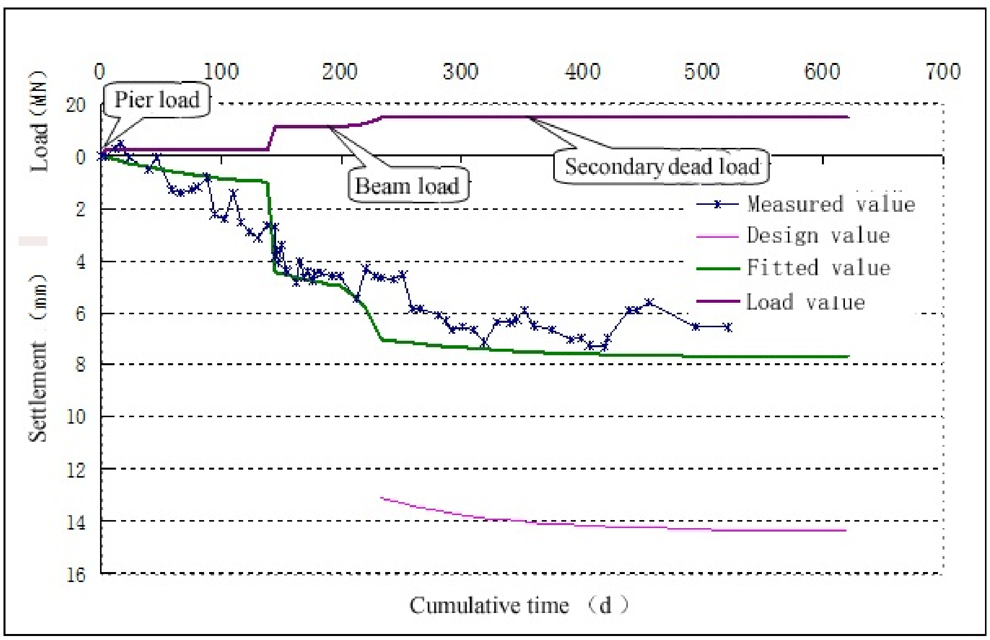

Figure 3: Settlement fitted curves for H110# pier

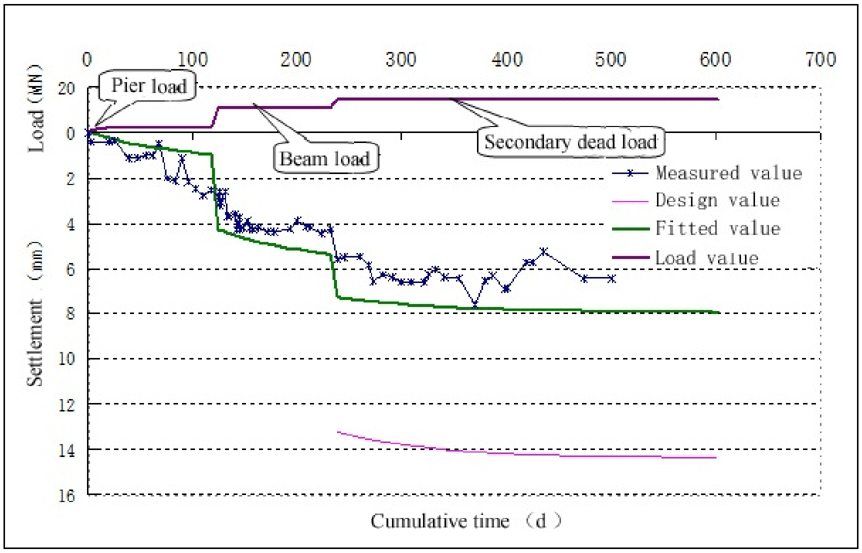

Figure 4: Settlement fitted curves for H111# pier

Based on the settlement observation results of Tianjin super-large bridge, the settlement curves of H109#, A400# and H111# were selected to fit and analysis. Firstly, the fitted process is briefly described. ①The α and B values are given in a reasonable range, the settlement prediction value S_t is calculated according to the fitted formula. ②According to the principle of least square method, the minimum value is the squares sum between the predicted value and the observed value, it is the control condition. Solving governing equations, the corresponding α and B values are obtained. ③The correlation coefficient is obtained between the predicted value and the observed value. According to the curves fitted analysis method, Figure 2~4 respectively give the 3 piers observation settlement, prediction settlement and design settlement, the comparison chart is as follows. The settlement curves fitted parameters for 3 typical piles of Tianjin super- large bridge are counted by table 1, we can see that the fitted degree of the combination prediction model is better, the correlation coefficient is more than 0.93. The pile bearing layer of Tianjin super-large bridge is mainly silty clay, the α value is related to the soil characteristics, construction process and so on. According to the table 1, the α value is about 0.01 for the silty clay. The B value is mainly related to the soil creep characteristics, it is recommended that the B value is about 0.8 for the silty clay.

Table 1: Analysis to settlement curves

Pier label	Pier height /m	Bearing layer	α	B	Correlation coefficient
H109	9	silty clay	0.0100	0.78	0.93
H110	9	silty clay	0.0103	0.82	0.95
H111	9	silty clay	0.0105	0.80	0.96

Cangde super-large bridge settlement prediction

The total length of Cangde super-large bridge is 105.81km and a total of 3092 piers. The soil around the pile is generally silty soil, silty clay, clay and silty sand. The pile end is located in the silty soil and silty clay.

There are 3092 bridge piers with settlement monitoring data. The settlement observation curves were analyzed and 322 effective curves were obtained. This paper will focus on the effective settlement curves, the combination prediction model is used to fit and predict the settlement. Due to the limited length of the paper, the correlation between the observed settlement and the predicted settlement is not listed.

Table 2 shows the fitted parameters statistics of 10 typical piles settlement curves for Cangde super-large bridge. From the table we can see that the fitted degree of the combination prediction model is better, the correlation coefficient is about 0.98. The pile bearing layer of Cangde super-large bridge is mainly silty soil and silty clay, the α value are from 0.01 to 0.02. The B value have some differences in different soil layers, according to the statistical results, the B value is recommended, it is about 0.80 for the silty soil and about 0.90 for silty clay and clay.

Table 2: Analysis to settlement curves

Pier label	Pier height /m	Bearing layer	α	B	Correlation coefficient
A272	5.5	silty clay	0.0145	0.88	0.98
B91	5.5	silty clay	0.0145	0.92	0.98
C66	15.5	silty soil	0.0105	0.72	0.97
D462	6	silty clay	0.0185	0.90	0.98
F48	6.5	silty clay	0.0145	0.93	0.99
F300	6	silty soil	0.0105	0.77	0.97
H89	5	silty soil	0.0145	0.80	0.97
H93	5	silty soil	0.0125	0.84	0.92
K297	5.5	silty soil	0.0145	0.82	0.98
K427	6	clay	0.0305	0.95	0.96

The settlement prediction and experiment results of the typical piers are accessible to the Tianjin super-large bridge and Cangde super-large bridge. The change process curves of the fitted curves and the measured curves are consistent, it basically reflects the law of deep soft-clay pile foundation settlement with time changing. The combination prediction method of considering deformation process index and long-term creep is suitable for deep soft-clay pile foundation. From table 1 and table 2 show that the α is in a certain range for two super-large bridges. Based on the statistical analysis of the survey data for two super-large bridges, the recommended α value for different soil type parameters are put forward. The α value is about 0.01~0.015 for the sandy soil and about 0.01 to 0.0305 for the non sandy soil. It is necessary to point out that the α are not only affected by the geological conditions, but also related to the load, construction process and other factors. At the same time, the B can reflect the creep characteristics, the difference is more obvious in different soil layers, the B value is about 0.80 for the silty soil and about 0.90 for silty clay and clay.

At present, many ordinary passenger dedicated railways and railway projects have been completed, which are about to be built and ready for construction are many in China. Especially, the bridge and culvert of the high speed railway project are set up a settlement observation mark. That is to say, there will be a large number of pile foundation settlement observation data basing on the different geological conditions, pier height and foundation in the future. The prediction method and the fitted parameters reflect the certain application value for Tianjin super-large bridge and Cangde super-large bridge, but application still has limitations. The next step will widely collect the available pile foundation settlement observation data, to further verify and perfect the calculation formula of the joint prediction method, giving a more reasonable and reliable range of the fitted parameters.

CONCLUSIONS

The combination prediction model is established by considering deformation process index method and long-term settlement prediction method, which can consider the loading effect and creep effect. Then the combination model is used to predict the settlement process of the typical piers for Tianjin super-large bridge and Cangde super-large bridge of Beijing-Shanghai high speed railway. The fitted curves well approach the actually measured curves, showing that the prediction method is right and practical. In addition, the fitted parameters of settlement curves are statistically analyzed, and the recommended value ranges of these parameters for various soils are provided. The research is practically significant to predict the long-term settlement process of soft-clay pile foundation without monitoring data.

Based on the statistical analysis of the survey data for two super-large bridges, in order to understand the pile foundation settlement characteristics in deep soft-clay, the α value for different soil type parameters are put forward. For the sandy soil, the α value is about 0.01~0.015, the B value is about 0.80; For the non sandy soil, the α value is about 0.01 to 0.0305, the B value is about 0.90. The results show that the α value are not only affected by the geological conditions, but also related to the load, construction process and other factors. At the same time, the B value can reflect the creep characteristics, the difference is more obvious in different soil layers.

ACKNOWLEDGEMENTS

This research is supported by the Science and technology of Beijing-Shanghai high speed railway (2008G031-B).

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Editor's note.
This paper may be referred to, in other articles, as:

Chen Fujiang, Ma Jianlin, Zhu Lin, Le Dawei: "Long-Term Settlement Process Prediction for Soft-Clay Pile Foundation Considering Creep Effect" *Electronic Journal of Geotechnical Engineering*, 2016 (21.20), pp 7045-7054. Available at ejge.com.