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Study on Settlement Prediction Model of High-Speed Railway Bridge Pile Foundation

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Abstract

Estimation of settlement for bridge pile foundation is critical to the construction of High-speed railway. In this paper, a great number of accurate and reliable settlement data were obtained via on-site long-term monitoring test, and on this basis the settlement laws of pile foundation and the characteristics of settlement-time curve were obtained: the settlement-time curve of bridge pile foundation in Beijing-Shanghai High-speed railway is a ladder-shaped under multiple load, and the conventional settlement prediction model can not reflect the entire process of the relationship between settlement and time. In order to overcome above shortcomings, a new settlement prediction model for bridge pile foundation was proposed in this paper, namely the Modified Exponential model (MEM). This model introduces the concept of load factor and clearly specifies a way to predict the post-construction settlement, and the comparisons of the predicted and measured settlement values are given by the Exponential model (EM), the Logistic model (LM) and the MEM, the results show that: the MEM yields better predictions of the test data than the other models due to it can take into account the measured data before erecting beam, and the level of agreement with the measured data is quite satisfying with its high predicted accuracy and little errors. At last, the influence of parameter beta at different stratum condition and loading combination were analyzed, and the recommended values were given by further gross error analysis and classification.

***Key Words*:** Settlement Prediction, The Modified Exponential Model, High-Speed Railway, Bridge Pile Foundation

1. Introduction

Scientific and rational prediction of settlement for bridge pile foundations is a key link in the process of High-speed railway construction. Recent years, with the rise of unballasted track on the bridges of High-speed railway, track structure must be highly stable and smooth-going, therefore the post-construction settlement and differential settlement of bridge foundations should be strictly controlled. In order to prevent excessive settlement in railway construction on soft ground, bridges are normally supported by pile foundations. Settlement behavior of pile foundations is the result of interactions of piles, caps and subsoil. Because of the limitations of various methods adopted to calculate ground deformation, the complexity of subsoil, and the multiformity of pile structures, load levels, construction process and arrangement of piles, it is nearly impossible to determine the profile of settlement of pile foundations versus time completely depended on theoretical calculations. Thus, it is significant and valuable to modelling the post-construction settlement prediction suited for different soil by field measurements.

Basically, the settlement prediction models which are commonly used can be classified into two categories: (i) the mathematical models to predict the whole process of settlement; typical examples include the Grey Theory by

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Yang et al. [1], Asaoka model by Wang et al. [2], Logistic model by Zhu and Zhou [3], Gompertz model by Yu and Liu [4], Richards model by Xiao and Chen [5], etc. This kind of models are widely used to reflect the whole process of settlement versus time, but the structure of these models is relatively complex, and they can not take fully into consideration the impact of load on the foundations, so it is usually impossible to obtain good agreement between the predicted settlement and field measurement under multilevel load. Therefore, the application is restricted to a certain degree. (ii) the models to predict the settlement after the completion of main project; Chen et al. [6] proposed the three-point modified exponential curve model for predicting subgrade settlements. Pan and Xie [7] studied the advantages and shortcomings of the Hyperbolic model based on the observational settlement data of eight practical projects. This kind of models are simple and easy, but the premise of application is to assume that the load is applied at one time which does not accord with the actual situation, therefore, the predicted values of these models agree well with the measurements in later period, whereas the fitting effect in earlier period is unstable.

In order to overcome the deficiencies of above common settlement prediction models, a new model for bridge pile foundations of High-speed railway was proposed in this paper, namely the Modified Exponential model. And the load factor is introduced to describe the effect of load on settlement. The model can take fully into consideration the immediate settlement derived from girder load. Obviously, the model demonstrates the importance being able to predict accurately the post-construction settlement profile using the settlement measurements during construction of Beijing-Shanghai High speed railway, which provides a new way of thinking for the settlement calculation and prediction of bridge foundations.

2. Development Regularity and Mechanism Analysis of Settlement for Bridge Pile Foundations

As shown in Figure 1, the Beijing-Shanghai High-speed railway, China, was planned and construction commenced in 2008, and 11357 pier monitoring tests had been carried out along the line. By the end of 2010, the settlement of bridge pile foundations had been stabilized.

After eliminating the curves that the overall settlement is less than 2 mm as well as the curves of settlement fluctuates strongly versus time, 805 accurate and reliable settlement data of pile group foundations were obtained via on-site monitoring test, and the basic settlement law of pile foundations and characteristics of settlement curves were summarized as follows:

(1) The phase of pouring pier shaft: The settlement of pile foundations is composed of elastic compression of the columns and the compression of subsoil beneath the columns, the settlement-time curve is approximately linear, while the vertical load acted on the columns is small and increases linearly versus time.

(2) The phase from finishing pouring pier shaft to the early period of erecting beam: The settlement is mainly made up of the compression of the subsoil under dead load.

(3) The phase of beam erection or cast-in-site: For the prefabricated beams, when the pier shaft is loaded vertically, e.g., by application of an erecting load, settlements will instantaneously produced by the weight of box girder. For the cast-in-site beams, the settlement increases approximately linear versus load. At this stage, the settlement is mainly made up of elastic



Figure 1. Station map for Beijing-Shanghai High-speed railway.

compression of the columns and the compression of subsoil beneath the columns.

(4) The phase from finishing beam erection or cast-in-site to the early period of laying unballasted track: The settlement of subsoil is mainly made up of the compression under dead load.

(5) The phase of laying unballasted track: The load increases approximately linearly with the construction of concrete base plates, CA mortar adjustment layers, railplates, rail fastenings and rail in order. At this stage, the settlement is mainly made up of elastic compression of the columns and the compression of subsoil beneath the columns, and the settlement rate slows significantly compared with the phase of beam erecting.

(6) The phase of operation: The load is mainly made up of the traffic load of train. The experiment and theoretical analysis by Lv et al. [8] shows that: the settlement of subsoil is mainly composed of creep settlement under dead load at this stage, while the compression of subsoil is basically completed, and the traffic load can not produce cumulative settlement. The typical load-settlement-time curves for bridge pile foundations of High-speed railway are shown in Figure 2.

3. Definitions of the Modified Exponential Model

According to Terzaghi's consolidation theory, the variation of pore water pressures versus time accords with the relationship of exponential curve, and the degree of consolidation defined by stress is equal to which defined by strain for linear elastic soils. Therefore, the soil compression process also accords with the relationship of exponential curve. Zeng et al. [9] suggested the degree of consolidation can be calculated as follows:

$$U = 1 - \alpha \exp(-\beta t) \tag{1}$$

where α and β are constants, respectively. t is the elapsed time after starting pouring the pier shaft.

According to the formula of average degree of consolidation, U can be defined as:

$$U = S_t / S_\infty \tag{2}$$

where S_t is the accumulative settlement of pile foundations at time t, and S_∞ is the final settlement of pile foundations.

Substituting Eq. (2) into Eq. (1), yields:

$$S_t = S_\infty [1 - \alpha \exp(-\beta t)] \tag{3}$$

Eq. (2) can be written as:

$$S_i = U_i S_\infty \tag{4}$$

where S_i is the accumulative settlement at time t_i, and U_i is the average degree of consolidation. When $t_2 = t_1 + \Delta t$, the corresponding settlement is $S_2 = S_1 + \Delta S$, and the functions can be written as follows:

$$\Delta S = U_2 S_\infty - S_1 \tag{5}$$

$$U_1 = 1 - \alpha \exp(-\beta t_1) \tag{6}$$

$$U_2 = 1 - \alpha \exp(-\beta t_1 - \beta \Delta t) \tag{7}$$

Substituting Eqs. (4), (6) and (7) into Eq. (5) yields:

$$\Delta S = S_\infty \alpha \exp(-\beta t_1)[1 - \exp(-\beta \Delta t)] \tag{8}$$

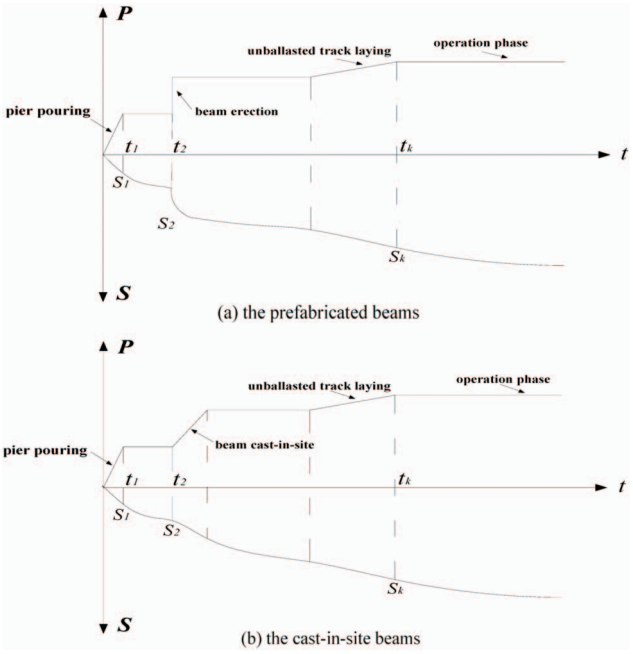


Figure 2. Load-settlement-time curves of bridge pile foundations.

where t_1 is the time of starting pouring the pier shaft, here looking upon the point of (t_1, S_1) as the origin of settlement-time coordinates (i.e. $t_1 = 0$), t_2 is the elapsed time after starting pouring the pier shaft (i.e. $\Delta t = t_2 - t_1$), ΔS is the increment of settlement versus Δt, and Eq. (8) can be simplified as:

$$S_t^{'} = S_\infty \alpha[1 - \exp(-\beta t^{'})] \tag{9}$$

where $S_t^{'}$ is the accumulative settlement at time $t^{'}$, and S_∞ is the final settlement.

It is convenient to express Eq. (9) when the superscript was ignored as follows:

$$S_t = S_\infty \alpha[1 - \exp(-\beta t)] \tag{10}$$

The process of above derivation agrees well with the derivation of the Exponential model, and the main difference is that the selected equations to calculate the degree of consolidation are slightly different. Indeed, a large number of case histories have indicated that the development of subsoil settlement accords with the exponential curve versus time. Generally, the Exponential model is strict with the monotonicity of field measurements, and can not directly be used to predict the ladder-type settlement under multilevel load as Figure 2. In order to overcome the deficiency and improve the performance of prediction, as well as in order to maintain the consistency of the model structure without adding new parameters, this paper introduces the load factor N_t / N_∞ to take the place of α, then a new settlement prediction model: the Modified Exponential model (MEM) is proposed as follows:

$$S_t = S_\infty \frac{N_t}{N_\infty}[1 - \exp(-\beta t)] \tag{11}$$

where t is the elapsed time after starting pouring the pier shaft, S_t is the accumulative settlement of pile foundations at time t, S_∞ is the final settlement of pile foundations, N_t is the accumulative load acted on the pile foundations at time t, N_∞ is the final accumulative load acted on the pile foundations, and β is the fitting parameter which is related to soil properties, arrangement of columns, construction technology, etc.

4. Solution of the Modified Exponential Model

The Modified Exponential model is a nonlinear model and difficult to solve directly, thus the least square method is used to calculate the parameters S_∞ and β in this paper, and the following objective function of absolute error is established between the predicted settlements and field measurements:

$$J = \sum_{i=1}^{n} (S_t - \widehat{S}_t)^2 \tag{12}$$

where J is the objective function of absolute error, S_t and $\widehat{S}_t$ are the predicted settlement and field measurements at time t respectively, and n are the observation times.

The specific calculation process can be expressed as follows:

(1) Solution of the load factor: Calculate the weight of piers, prefabricated beams, bed plates, railplates and other secondary dead load respectively, then the load factor N_t / N_∞ of different phases can be obtained;

(2) Establish the function between S_t and t based on Eq. (11) for any given value of β and S_∞. Thereby, the settlement at different time and $J = \sum_{i=1}^{n} (S_t - \widehat{S}_t)^2$ can both be solved;

(3) While J gets the minimum value, the value of β and S_∞ can be calculated based on the least square method, and subsequently the expression of the Modified Exponential model can be obtained;

(4) Get the predicted settlement S_t at different time t.

5. Application to Case History

5.1 General Description

Along the route of the Beijing-Shanghai High-speed railway, Beijing, Tianjin, Qingcang, Cangde, Deyu and Yuji super large bridges are selected as the typical test sections.

Before bridge superstructure constructed, the ground was improved by the installation of bored piles. The columns had a diameter of about 1.2 m and a length of about 50 m. They were arranged in a square pattern with

a spacing of 3.4 m. The bearing courses at pile end are mainly silty clay and clay layer.

In this paper, 805 sets of settlement data are used to validate and calibrate the EM (which referred to the Exponential model), LM (which referred to the Logistic model) and MEM (which referred to the Modified Exponential model) by comparing their predictions with measurements, and settlement observation from pouring the pier to the operational phase was lasted for nearly two years, here, only 10 typical sections are listed in Table 1 due to space limitations.

As presented in Table 1:

(1) The prediction accuracy of three models is high with that the correlation coefficients are more than 0.92. In comparison, the average value of the correlation coefficients based on the MEM is highest, the LM is lower, and the EM is lowest. Meanwhile, the mean absolute percentage error of the MEM is lowest, the LM is higher, and the EM is highest.

(2) In comparison, the predicted values of the MEM are closest to the measured values, the LM is further, and the EM is furthest. Therefore, the comparisons between predictions and measurements described above indicate that the level of agreement with the measured data of the MEM is quite satisfying with its higher predicted accuracy and less errors.

5.2 Analysis of Typical Section

Take the section C66 and B87 for example, the comparison of the settlement curves are shown as Figures 3 and 4.

Table 1. Comparison of predicted and measured settlements of different models

Case	Section	Settlements (mm)				Correlation coefficient			Mean absolute percentage error (%)		
		Measured	Predicted								
			EM	LM	MEM	EM	LM	MEM	EM	LM	MEM
1	A397	6.350	15.000	8.291	9.262	0.859	0.926	0.950	79.226	55.913	42.231
2	A400	5.650	15.000	5.265	6.545	0.869	0.977	0.958	173.728	47.417	60.777
3	B87	7.391	6.968	5.838	7.714	0.944	0.951	0.980	487.653	276.338	194.889
4	B91	6.002	15.000	5.310	5.910	0.921	0.965	0.976	286.924	56.448	123.238
5	C66	5.524	6.807	4.390	5.592	0.934	0.933	0.970	52.801	38.631	49.758
6	H93	5.670	6.472	5.772	5.930	0.934	0.945	0.919	20.660	22.595	20.869
7	J186	3.680	3.580	3.427	3.512	0.963	0.954	0.962	17.183	23.197	22.364
8	J226	4.810	4.752	4.738	4.589	0.941	0.918	0.952	17.999	21.117	12.726
9	J227	4.360	4.259	4.240	4.072	0.924	0.902	0.937	16.593	18.455	13.692
10	K297	5.040	5.406	4.820	4.918	0.923	0.965	0.986	302.479	130.965	79.369
Average value		–	–	–	–	0.920	0.943	0.959	145.525	99.108	50.014

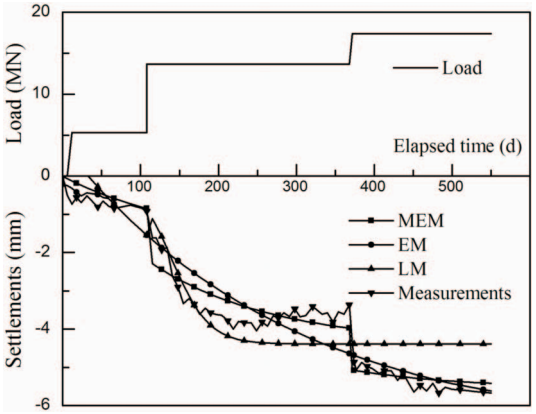


Figure 3. Comparison of the settlement curves for section C66.

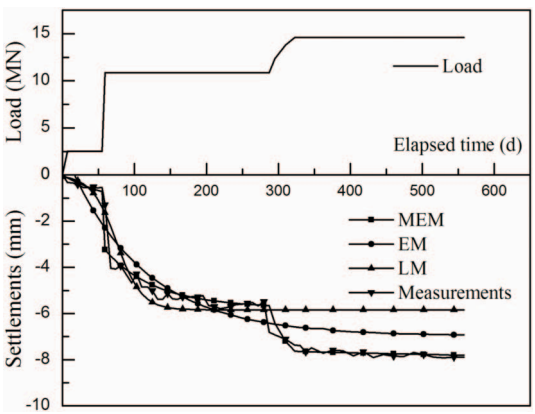


Figure 4. Comparison of the settlement curves for section B87.

As shown in Figures 3 and 4, the load at different construction stages may induce a certain mutations of settlements. The measured settlement-time curves are described better by MEM than by EM or LM under multiple load.

5.3 Selection of Model Parameters

The results of above typical sections of pile group foundations shows that: the level of agreement between the predicted and measured settlement is quite satisfying by using MEM, and the obligation to validate and calibrate the correctness and practicability of this model by above analysis is acknowledged. Indeed, the parameter beta in this model is not only related with the load and time, but also related to the formation conditions. In order to verify the effectiveness of beta and get the recommended values, Dixon criterion, which is suitable for small sample space (generally less than 30 samples), is selected to analyze the gross error in this paper. Since the Dixon criterion is just applicable for normal distribution, the testing sections under similar load are chosen as a group in the paper. The selected significance level in the calculation is 0.01 (i.e. the confidence level is 99%), and the recommended values of model parameter beta are shown in Table 2.

In conclusion, when the bearing course at pile end is located at silty layer, the recommended values of β is less than 0.01, and the larger the load, the smaller the value of β.When the bearing course at pile end is located at clay layer, the recommended values of β is more than 0.01, and the larger the load, the smaller the value of β.

6. Conclusions

Based on the current study, the following conclusions may be drawn:

(1) The basic settlement law of pile foundations and characteristics of load-settlement-time curves are summarized by analyzing and classifying the field measurements as follows: the curves show a significant ladder-type under multiple load.
(2) The Modified Exponential model is established by introducing the concept of load factor based on the settlement characteristics of bridge pile foundations in this paper, and the process of model formulation is also introduced.
(3) Applied the Modified Exponential model to the settlement prediction of bridge pile foundations for Beijing-Shanghai High-speed railway by comparing their predictions with measurements, the comparisons clearly demonstrate that this model is quite satisfying for predicting the settlement of ladder-type curves under multiple load, and the predicted accuracy is higher than the EM or LM.
(4) The recommended values of model parameter beta of the Modified Exponential model for different soils and load are given by further gross error analysis and classification.
(5) The Modified Exponential model uses a load factor to reflect the percentage of load applied to the pile foundation, and the model demonstrates the importance being able to predict accurately the post-construction settlement profile using the monitoring data during construction. However, if the main project has been completed, the model has no obvious advantage to predict the post-construction settlement by using the data after construction. The model provides a new way of thinking for the settlement calculation and prediction of bridge foundations, however, whether the model is applicable to other projects should be clarified by further study.

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Table 2. Recommended values of model parameter beta

Bearing course at pile end	Change interval of load (MN)	Change interval of β	Mean of β	Instructions of eliminating
Silty clay	13.7–14.6	0.0049~0.0123	0.0092	180 sets of data, 7 sets are eliminated
	14.7–21.1	0.0037~0.0109	0.0068	220 sets of data, 8 sets are eliminated
Clay layer	13.5–14.4	0.0115~0.0371	0.0209	200 sets of data, 3 sets are eliminated
	14.5–16.0	0.0079~0.0255	0.0148	205 sets of data, 3 sets are eliminated

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