

## Measurement and Analysis of High-speed Railway Subgrade Settlement in China: A Case Study

<sup>1,2</sup> Qulin TAN, <sup>1</sup> Leijuan LI, <sup>1</sup> Senlin WANG

<sup>1</sup> Photogrammetric Engineering & Remote Sensing, School of Civil Engineering, Beijing Jiaotong University, Beijing, 100044, China

<sup>2</sup> Beijing Key Laboratory of Track Engineering, Beijing Jiaotong University, Beijing 100044, China

<sup>1</sup> Tel.: 086-010-51688207, fax: 086-010-51683764

E-mail: qltanbjtu@163.com

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**Abstract:** Subgrade is an important component of railway engineering construction, which supports the upper loads of tracks and trains. Subgrade stability directly affects the high-speed train safety and passenger comfort. With the rapid development of China's high-speed railway, it put a very high requirement for track smoothness, and thus the requirements of subgrade stability and deformation control become very stringent. In the paper, we studied the measurement methods, instruments, observation point set, observation frequency, precision and data prediction analysis etc. Using the subgrade settlement measured data of Beijing-Shanghai high-speed railway as a case study; we analyzed the relationship between the subgrade settlement and time, and applied hyperbolic model, exponential model and Poisson model to predict subgrade post-construction settlement. The results show that cumulative settlement of subgrade measuring point is 6.4 mm from the beginning to 118<sup>th</sup> day after roadbed filling construction, and the sedimentation rate becomes steady at 0.001 mm/d. Comparative analysis shows that the hyperbolic model has the best fitting performance among the three curve regression models. And the predicted roadbed post-construction settlement of 3.22 mm has met the subgrade requirements for ballastless-track laying. *Copyright © 2014 IFSA Publishing, S. L.*

**Keywords:** High-speed railway, Subgrade, Settlement, Deformation monitoring, Prediction.

### 1. Introduction

Railway subgrade, which directly supports train and rail, is an important part of railway-line construction engineering project. So the geotechnical structure of railway subgrade, which formed through excavation or filling, must have enough engineering stability and very small permanent deformation to meet track laying and safe operation conditions [1-3]. Subgrade post-construction settlement is the residual settlement under the loads of subgrade, track and train after track laying engineering completion. That is the difference between the total settlement amount

and the settlement at the beginning of track laying. Therefore, the subgrade settlement amount greatly influences the smoothness of high-speed railway. The smaller the post-construction settlement is, the more conducive to the safe operation of the high-speed railway line. To ensure the safety and comfort of high-speed railway operation, the post-construction settlement amount of high-speed railway subgrade, particularly for ballastless track line, should be generally controlled within 2~3 cm, almost 'zero settlement' [1, 3]. At present, China's high-speed railways mostly adopt non-ballasted track to meet the high-speed driving safety and comfort. Before laying

non-ballasted track, subgrade settlement deformation must be systematically evaluated. Engineers must confirm that subgrade settlement deformation assessment can meet the requirements for ballastless track laying. When the predicted settlement value is within the height adjustment range of fasteners (typically 15 mm), the work of ballastless track laying can be allowed to begin [1].

So, assessment of subgrade settlement observation and prediction is very critical for ballastless track laying. Also for this reason, high-speed railway roadbed settlement deformation analysis becomes an important issue in recent years due to lots of high-speed railway engineering construction projects in China [3-12]. Currently, some researchers have proposed the concept of integration of subgrade settlement observation and prediction for evaluation of ballastless high-speed railway, and developed data management and analysis integrated system for settlement deformation observation analysis and assessment [4, 7].

Settlement prediction methods are generally divided into three categories. The first category is classical hierarchical sum method to predict final settlement by calculating the consolidation degree. The second category is the numerical calculation method according to consolidation theory and various soil constitutive models, which the final settlement is calculated by the difference method, finite element method and boundary element methods. The first and second class methods involve many parameters, which are derived through a lot of tri-axial tests and unidirectional consolidation test. So it is not easy to apply in practical engineering.

The third category belongs to regression analysis method to predict the subgrade settlement based on measured data. The methods include: hyperbolic curve model, exponential curve method, the Poisson curve, three-point method, Hoshino method, parabolic method, gray theory and artificial neural network method. Regression analysis methods are currently the most commonly used methods in deformation predicting field. A large number of engineering experience shows that the performance of settlement prediction method based on the measured data relies on actual settlement deformation characteristics and observation data quality of specific engineering project. Choosing an appropriate curve model for settlement prediction analysis is very important in order to calculate accurate post-construction settlement.

Aiming at the issue of measurement and analysis of high-speed railway roadbed settlement deformation, we studied the measurement method, instruments and observation points for subgrade settlement, and analyzed the observation time, the accuracy requirements, especially subgrade post-construction settlement prediction analysis. A case study combined with the Beijing-Shanghai high-speed railway settlement monitoring data during subgrade construction period was given in the paper. We analyzed the relationship between time and the

subgrade settlement amount, and applied the settlement prediction models of Poisson curve, hyperbolic curve and exponential curve to predict subgrade post-construction settlement.

## **2. Measurement Methods, Instruments and Observation Point Setting**

Currently, subgrade settlement observation work of passenger dedicated railway line is mainly related to surface settlement observation and ground subsidence observation. Leveling is the most used measurement method [13, 14]. The settlement observation piles are located in the surface center, the left and right side shoulder of the railway subgrade. The settlement board is buried in the ground base table with a connected external surface measuring mast. According to the requirements of deformation measurement accuracy and frequency, the measuring point elevations of observation piles and external surface mast are acquired by periodic level observing. The subgrade surface or ground settlement magnitude is derived by the comparison of two adjacent measurement elevations (i.e., elevation difference). Among them, the subgrade surface settlement amount is the basis to determine whether the post-construction settlement requirements are met.

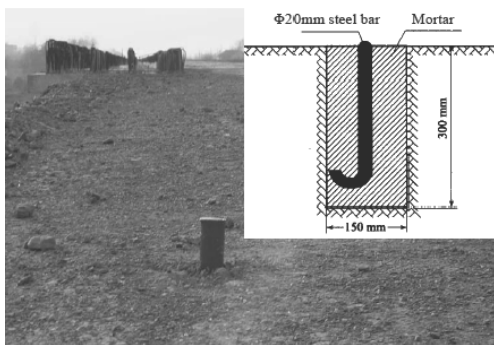
Observation points for settlement measurement include benchmarks, work basis points and settlement observation points. Benchmarks should be selected at a stable position outside the deformation region for long-term preservation (the national first-class leveling measurement). Working basis points should be selected at a relatively stable position in close to observation target and easy to connection leveling (the national second-class leveling), and regularly checked. Benchmarks and work basis points constitute settlement observation control network, which are used as control points for long-term settlement observation.

Deformation observation precision depends on deformation allowable value, the engineering design and observation purposes. The precision of high-speed railway roadbed settlement deformation monitoring should be designed that the settlement observation error is less than the 1/10 to 1/20 of the deformation allowable value. Because post-construction roadbed settlement for non-ballasted track shall comply with fastener' adjustment range and vertical curve smoothness requirements, the post-construction settlement cannot exceed 15 mm. When settlement is relatively uniform and vertical curve radiuses meet the requirements after track surface height adjustment, the allowable post-construction settlement is 30 mm. So settlement deformation observation should be carried out under the national second class leveling measurement accuracy requirements, using precision level instrument (DS05 or DS1 type) and indium-watt level ruler [13, 14]. The error of elevation leveling for subgrade

settlement observation point is  $\pm 1.0$  mm. The minimum reading is 0.1 mm, and the standard error of height difference for adjacent observation points is 0.5 mm. Roadbed settlement deformation measurement instruments, settlement observation post and settlement plate (including floor plate, metal measuring rod and protective tube) are shown in Fig. 1, and a schematic distribution diagram of reference datum point, the working base point and settlement deformation observation point is shown in Fig. 2.



(a) Level and ruler.



(b) Settlement observation pile.



(c) Settlement plate.

Fig. 1. Settlement observation equipment & instruments.

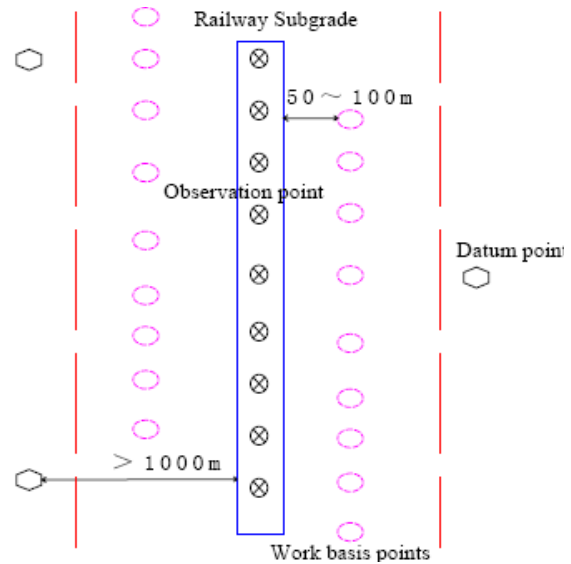


Fig. 2. Schematic distribution diagram of measuring points.

Subgrade settlement observation section and observation points should be arranged according to the engineering structure, topographic and geologic conditions, foundation treatment methods, embankment height, preloading and other specific circumstances [15]. The spacing of subgrade settlement observation section is generally not more than 50 m, where can be relaxed to 100 m for the cuttings and embankments of less than 5 m height with flat, uniform geological conditions. The observation section spacing for roadbed basement subsidence is generally not more than 200 m. Observation section should be properly increased distribution density in transition geotechnical structures and under topographic and geologic changing conditions. In order to reflect the true situation of subgrade settlement, settlement observation point should be buried at locations where mostly reflects the settlement characteristics and facilitates field observation work. The arrangement of subgrade settlement deformation observation points usually is: 1) For general embankments and cuttings, every observation section includes three subgrade settlement observation piles (set in the center, two shoulder sides of the subgrade) and one settlement panel (arranged on two-lane roadbed center), respectively. 2) For soft and loose soil embankments and cuttings, every section includes a settlement profiler tube, three settlement observation piles (also set in the center, two shoulder sides of the subgrade), one settlement plate (also arranged on two-lane roadbed center) and two displacement piles. Here, we just discussed and analyzed the subgrade surface settlement.

### 3. Frequency of Observation

To reflect the deformation process systematically, and do not miss a moment of deformation occurrence, but also plan scientifically to reduce the monitoring

workload, it is very important to work out a reasonable settlement observation time table and observation frequency for settlement deformation monitoring project. Generally deformation monitoring frequency should be designed according to the monitoring purposes, the size of the deformation amount and deformation rate and other factors. Subgrade settlement observation begins from the beginning of roadbed filling, and completes on 12 months after the non-ballasted track laying. Table 1 shows the observation frequency requirements issued by the china's railway administrative department.

**Table 1.** Observation frequency requirements for subgrade settlement measurement.

Stages	Observation Frequency	
	General	
Filling or Heaped Load	General	1 time/day
	Settlement mutation	2~3 time/day
	Long time interval	1 time/3 day
Subgrade construction completion	First month	1 time/week
	2 <sup>nd</sup> and 3 <sup>rd</sup> month	1 time/2 week
	4 <sup>th</sup> month and later	1 time/month
Erecting machine (beam carrier) pass	Entire process	1 time/day 1 time/3 days 1 time/week
After non-ballasted track laying	First month	1 time/2week
	2 <sup>nd</sup> and 3 <sup>rd</sup> month	1 time/month
	4 <sup>th</sup> ~ 12 month	1 time/3 months

Subgrade settlement observation can be divided into four stages. The first stage is the settlement observation during subgrade filling construction. The second stage is the deformation observation and natural placement period after completion of subgrade filling construction or preload (usually not less than six months). In this stage, subgrade surface settlement, partial settlement of roadbed filling construction and subgrade ground base subsidence should be monitored systematically. According to monitoring results, the completion time of the final settlement is analyzed and evaluated, and the post-construction settlement is predicted. If observational data are insufficient to assess, or when the settlement prediction value does not meet the design requirements, the observation work time should be extended. Or it is necessary to take measures to accelerate or control settlement. The third stage is the construction monitoring of non-ballasted track laying period. And the fourth stage is observation during trial operation after the laying of tracks.

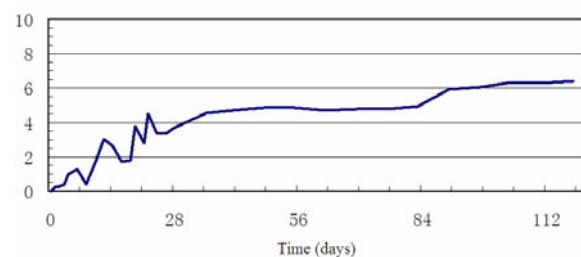
In the process of implementing the settlement observation, observation time interval should be adjusted according to the settlement value and the

sedimentation rate of the foundation. When the settlement is greater than 4 mm between two consecutive observations, the observation frequency should be increased. When the settlement mutation, groundwater and rainfall change in the external environment, the frequency of observation also should be increased. Each time node of subgrade construction (including preloading subgrade soil, uninstalling pre-compacted soil, beam carrier or erecting machine passing, ground-bed surface construction, rail-base plate construction, track slab laying, etc.) should have the settlement observation data. In the observing process, settlement curve should be drawn out, and observation should continue until the project is completed and accepted.

#### 4. Prediction Analysis: A Case Study

Before non-ballasted track laying, the main purpose of predictive analysis on the roadbed settlement deformation observation data is to determine whether the subgrade condition can meet non-ballasted track laying requirements by comparing the predicted settlement values and control standards. In the paper, we selected one dataset of 31 observation times before non-ballasted track laying at a subgrade surface measuring point along Beijing-Shanghai high-speed railway (mileage DK934+350--DK988+440), to forecast post-construction settlement deformation. The settlement data are showed in Table 2. According to the requirements of 'Technique guide for passenger-dedicated railway non-ballasted track laying condition assessment', the predicted subgrade final settlement and post-construction settlement should be calculated using multiple curvilinear regression analysis, and the relationship curve between the settlement and the time should be built based on actual observation data.

From Fig. 3, the main settlement deformation characteristic of the observation point is that settlement deformation significantly increased during the roadbed construction.



**Fig. 3.** The actual settlement curve of one measuring point during the first and second observation stage.

After filling is completed, the settlement rate gradually decreases, settlement deformation within six months has been basically stable. Settlement

process appears smoothly with convergence curve law. For that settlement deformation trend has been basically stable, subgrade settlement observation period may be relaxed to four months or more, allowing it to carry out settlement evaluation in advance.

**Table 2.** Settlement observation data of one measuring point during the first and second observation stage.

Times	Days	Current Settlement (mm)	Cumulative settlement (mm)	Settlement velocity (mm/d)
1	0	0.00	0.00	0.000
2	1	0.25	0.25	0.250
3	2	0.04	0.29	0.020
4	3	0.11	0.40	0.037
5	4	0.60	1.00	0.150
6	6	0.27	1.27	0.045
7	8	-0.87	0.40	-0.109
8	10	1.25	1.65	0.125
9	12	1.36	3.01	0.113
10	14	-0.39	2.62	-0.028
11	16	-0.91	1.71	-0.057
12	18	0.09	1.80	0.005
13	19	1.99	3.79	0.105
14	21	-1.02	2.77	-0.049
15	22	1.73	4.50	0.079
16	24	-1.15	3.35	-0.048
17	26	0.00	3.35	0.000
18	28	0.35	3.70	0.013
19	35	0.86	4.56	0.025
20	41	0.13	4.69	0.003
21	48	0.16	4.85	0.003
22	55	0.00	4.85	0.000
23	62	-0.13	4.72	-0.002
24	69	0.08	4.80	0.001
25	76	-0.02	4.78	0.000
26	83	0.17	4.95	0.002
27	90	1.00	5.95	0.011
28	97	0.12	6.07	0.001
29	104	0.26	6.33	0.003
30	111	-0.02	6.31	0.000
31	118	0.09	6.40	0.001

**4.1. Hyperbolic Model**

Hyperbolic method is commonly used in settlement prediction. The basic equation of hyperbolic model is:

$$S_t = S_0 + \frac{t - t_0}{\alpha + \beta(t - t_0)}, \tag{1}$$

where  $S_0$  is the settlement value at  $t_0$ ,  $S_t$  is the settlement value at  $t$ ,  $\alpha, \beta$  are the undetermined parameters. The formula (1) is rewritten as:

$$\frac{t - t_0}{S_t - S_0} = \alpha + \beta(t - t_0), \tag{2}$$

From the above equation,  $\alpha, \beta$  are the slope and intercept of  $\frac{t - t_0}{S_t - S_0} - (t - t_0)$  relationship graph.

Thus, we can obtain:  $\alpha = 5.6267, \beta = 0.1039$ .

Thereby, the settlement value at any time is:

$$S_t = S_0 + \frac{t - t_0}{5.6267 + 0.1039(t - t_0)}, \tag{3}$$

When  $t \rightarrow \infty$ , we have the final settlement as:

$$S_\infty = S_0 + \frac{1}{\beta} = 0 + \frac{1}{0.1039} = 9.6246mm, \tag{4}$$

**4.2. Poisson Growth Curve Model**

Poisson growth curve of settlement versus time using the following expression:

$$S_t = \frac{c}{1 + ae^{-bt}}, \tag{5}$$

where  $S_t$  is the settlement prediction value at  $t$ ,  $a, b$  and  $c$  are the undetermined constants. We can use the time series data to derive the above three parameters in order to establish the Poisson curve equation to predict. Given that the first part is:  $t=1,2,3,\dots,r$ ; the second part is:  $t=r+1,r+2,r+3,\dots,2r$ ; and the third part is:  $t=2r+1,2r+2,2r+3,\dots,3r$ . Let  $S_1, S_2$  and  $S_3$  be as the sum of reciprocal value, respectively, then:

$$S_1 = \sum_{t=1}^r \frac{1}{S_t}, S_2 = \sum_{t=r+1}^{2r} \frac{1}{S_t}, S_3 = \sum_{t=2r+1}^{3r} \frac{1}{S_t}, \tag{6}$$

For eq. (5) and (6), we can get equations (7), (8) and (9):

$$b = \frac{\ln \frac{(S_1 - S_2)}{(S_2 - S_3)}}{r}, \tag{7}$$

$$c = \frac{r}{S_1 - \frac{(S_1 - S_2)^2}{(S_1 - S_2) - (S_2 - S_3)}}, \tag{8}$$

$$a = \frac{(S_1 - S_2)^2(1 - e^{-b})c}{[(S_1 - S_2) - (S_2 - S_3)]e^{-b}(1 - e^{-rb})}, \tag{9}$$

Given  $r=3$ , then we can get:

$$S_1 = \frac{1}{4.72} + \frac{1}{4.80} + \frac{1}{4.78} = 0.629,$$

$$S_2 = \frac{1}{4.95} + \frac{1}{5.95} + \frac{1}{6.07} = 0.535, \text{ and}$$

$$S_3 = \frac{1}{6.33} + \frac{1}{6.31} + \frac{1}{6.40} = 0.473.$$

So, we can derive that:

$$b = \frac{\ln \frac{0.094}{0.062}}{3} = 0.139,$$

$$c = \frac{r3}{0.629 - \frac{(0.094)^2}{0.094 - 0.062}} = 8.498, \text{ and}$$

$$a = \frac{0.094^2(1 - e^{-0.139}) \times 8.498}{(0.094 - 0.062)e^{-0.139}(1 - e^{-3 \times 0.139})} = 1.028.$$

Thereby the settlement value at any time is:

$$S_t = \frac{8.498}{1 + 1.028e^{-0.139t}}, \quad (10)$$

When  $t \rightarrow \infty$ , we have the final settlement as:

$$S_\infty = \frac{c}{1} = 8.498 \text{ mm}. \quad (11)$$

### 4.3. Exponential Curve Model

Assuming at any time, soil average consolidation degree is an exponential function of time, the exponential curve model based on the consolidation degree theory is:

$$S_t = S_\infty(1 - Ae^{-Bt}), \quad (12)$$

where  $S_\infty$  is the final settlement  $S_t$  is the settlement value at  $t$ ,  $A$  and  $B$  are the undetermined parameters. Since there are three unknowns in the above formula. We can select any three points:  $(t_1, S_1), (t_2, S_2), (t_3, S_3)$  from settlement-time curve, and let  $t_2 - t_1 = t_3 - t_2$ . Using the three points in equation (11), we can obtain:

$$S_1 = S_\infty(1 - Ae^{-Bt_1}),$$

$$S_2 = S_\infty(1 - Ae^{-Bt_2}), \text{ and}$$

$$S_3 = S_\infty(1 - Ae^{-Bt_3}).$$

Thus, we can derive:

$$S_\infty = \frac{S_3(S_2 - S_1) - S_2(S_3 - S_2)}{(S_2 - S_1) - (S_3 - S_2)},$$

$$S_\infty = \frac{S_1 S_3 - S_2^2}{S_1 + S_3 - 2S_2},$$

$$B = \frac{1}{t_2 - t_1} \ln \frac{S_2 - S_1}{S_3 - S_2},$$

$$1 - \frac{S_1}{S_\infty}$$

$$A = \frac{S_\infty}{e^{-Bt_1}}.$$

Given the three points as (76, 4.78), (97, 6.07) and (118, 6.40), then we have:

$$S_\infty = 6.660 \text{ mm},$$

$$B = \frac{1}{90 - 62} \ln \frac{5.95 - 4.72}{6.40 - 5.95} = 0.0359, \text{ and}$$

$$A = \frac{1 - \frac{4.72}{6.660}}{e^{-0.0359 \times 62}} = 2.698.$$

Thereby the settlement value at any time is:

$$S_t = 6.660 \times (1 - 2.698e^{-0.0359t}), \quad (13)$$

### 4.4. Comparative Analysis

In the process of solving practical problems, the criteria of whether the regression curve fitting well or not under the same parameter conditions, is that the closer the fitted values is to observation value, then the better the fitness is. Consider the observed and predicted values as points of N-dimensional space, if the distance between the observed and predicted values is smaller, the estimation is used to predict better. Thus, the goodness of fit index can be defined as correlation coefficient R:

$$R = 1 - \sqrt{\frac{\sum (s_t - \hat{s}_t)^2}{\sum s_t^2}}, \quad (14)$$

For the original data and the fitted data, it is clear that the goodness of fit index is less than or equal to 1. The index organically combines the sum of squared residuals with relative error, which has clear geometric meaning and simple calculation. The closer to 1 of this value is, the better the goodness of fit curve. Comparison of the measured and predicted settlement curves, analysis result shows that hyperbolic model predictions fit better and has the highest correlation coefficient. The deviation of Poisson predicted settlement value is large. Fig. 4 shows the curves of measured and predicted settlement value versus observation times.

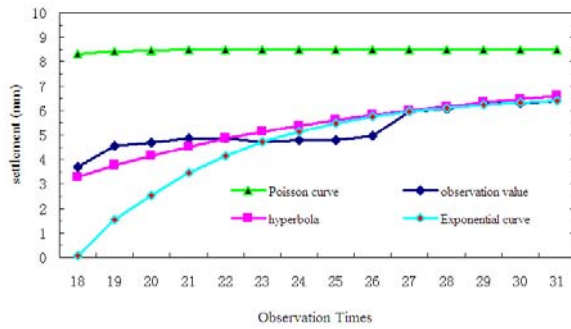


Fig. 4. Curves of measured and predicted settlement value.

Non-ballasted track laying condition assessment criteria should meet the following requirements: 1) Based on actual observation data, more than one regression curve analysis models must be adopted to determine the trend of settlement deformation, the correlation coefficient of regression curve should not be below 0.92. 2) The reliability of settlement prediction should be validated, the forecast deviation of 3-6 months interval cannot be greater than 8 mm. 3) The final settlement prediction before track laying should meet the basic requirements of its predictive accuracy, that is, the settlement from the roadbed filling or after preloading and final settlement prediction value should meet the following condition:  $S_t / S_\infty \geq 75\%$ , where  $S_t$  is the actual settlement from subgrade filling or preloading completion,  $S_\infty$  is the predicted final settlement from subgrade filling or preloading completion. 4) When the settlement prediction model meets the relevant requirements, we can calculate the predicted total or final settlement. In the case of laying time is determined, engineers can get the current total settlement amount before the non-ballasted track laying based on the measured data, then the post-construction settlement prediction can be derived.

Settlement data prediction analysis using hyperbolic, Poisson and exponential curve methods, shows that all the predicted post-construction settlement values are less than 15 mm with 3.22 mm, 2.10 mm, 0.26 mm respectively, all correlation coefficients are greater than 0.92. But since the settlement observation data were obtained during only five months after preloading, the reliability cannot be further verified.

## 5. Conclusions and Discussions

Subgrade post-construction settlement control is the key to lay ballastless track. Before ballastless track laying, roadbed deformation should be systematically assessed to ensure the roadbed construction settlement and deformation meets the design requirements. The main purpose of subgrade settlement observation is to predict the late settlement rate, the total settlement amount, post-construction settlement value by regression curve fitting analysis

based on the settlement deformation observation data during construction period. Typically subgrade filling or preload completion, the observed period should not be less than six months to ensure that the roadbed completes most of settlement. When the observed data are insufficient to assess or the settlement does not meet the design requirements, it is necessary to extend observation time or to take measures to accelerate or control subgrade settlement. To ensure the forecast accuracy, at least two curve fitting methods should be selected to calculate the predicted value for each measuring point during the forecast analysis. In order to strictly control the subgrade post-construction settlement, the maximum settlement point on subgrade section can be selected as sample data to evaluate.

In general, from the later part of settlement-time curve to extract any two points' data (in this case the settlement deformation should be stable or change very little), we can calculate the ideal settlement deformation and settlement amount at any time. But if the settlement deformation is still in the early stages of a larger change, which is in front of hyperbolic curve, then the direct use of this method will appear larger deviations. Therefore, the actual applications require enough monitoring time, usually at least six months or more, before the use of hyperbolic settlement prediction method.

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## References

- [1]. Technical guidelines for assessing passenger dedicated railway ballastless track laying conditions, *Academy of Railway Sciences, China Railway Press*, 2008, pp. 5-7.
- [2]. Ballastless track railway construction technical guide, *China Railway First Group Co., Ltd., China Railway Press*, 2007, pp. 15-20.
- [3]. S. X. Chen, J. Song, Q. N. Zhou, Theory and practice for high-speed railway settlement deformation observation assessment, *China Railway Press*, 2010.
- [4]. C. L. You, The integration concept of ballastless track post-construction settlement deformation observation and assessment, *Journal of Railway Science and Engineering*, Vol. 102, Issue 3, 2007, pp. 25-28.
- [5]. H. Q. Cao, Study on the deformation control and observation techniques for ballastless track railway subgrade settlement, *Railway Construction Technology*, No. 12, 2009, pp. 85-88.
- [6]. G. J. Ju, Ballastless track railway subgrade settlement observation and assessment, *Journal of Railway Standard Design*, No. 8, 2009, pp. 19-22.
- [7]. X. Z. Zhang, C. Mo, P. X. Ma, System design and implementation of assessing high-speed railway

- settlement observation and prediction, *Railway Survey*, No. 5, 2010, pp. 1-4.
- [8]. S. X. Chen, X. Y. Wang, X. C. Xu, A new method of railway passenger dedicated line subgrade settlement prediction, *Rock and Soil Mechanics*, Vol. 31, No. 2, 2010, pp. 478-452.
- [9]. J. J. Mu, X. L. Weng, Wuhan-Guangzhou passenger dedicated line for settlement observation and settlement estimation, *Railway Construction Technology*, No. 5, 2008, pp. 31-37.
- [10]. L. H. Xie, Observation and analysis of passenger dedicated railway soft soil subgrade settlement, *Railway Construction Technology*, No. 1, 2009, pp. 170-173.
- [11]. G. Y. Wang, Wuhan-Guangzhou passenger dedicated line embankment settlement monitoring system and settlement prediction, *Journal of Railway Engineering Society*, No. 5, 2009, pp. 5-7.
- [12]. H. G. He, Subgrade settlement monitoring and components buried technique of Wuhan-Guangzhou railway passenger dedicated line, *Journal of Railway Standard Design*, No. 1, 2010, pp. 28-32.
- [13]. H. Sun, Application of high precision electronic level in settlement observation, *Journal of Electric Power Design*, No. 6, 2007, pp. 32-34.
- [14]. Code for high-speed railway engineering surveying, *China Railway Second Engineering Group Co., Ltd., China Railway Press*, 2010, pp. 89-91.
- [15]. Passenger dedicated railway subgrade construction technical guide, *China Railway Fourth Bureau Group Co., Ltd., China Railway Press*, 2005, pp. 40-41.

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