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Research paper

A new method for predicting consolidation settlements of soft ground based on monitoring results

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Abstract: Excessive settlement or differential settlement of subgrade will lead to the deterioration of line operational conditions, the reduction of passenger comfort, and even endanger the safety of traffic. Therefore, it is of great significance to study the settlement prediction of subgrade. In order to predict the settlement of foundation under the next level of loading earlier during the embankment construction process, a new method of predicting settlement of soft soil subgrade is proposed. Firstly, based on monitoring results of soft soil foundation, the consolidation parameters of soil layer are back-calculated according to the three-point method. Then, combined with the theory of the consolidation degree of graded loading, the formula that can predict settlement under different loading conditions are derived. Eventually, the practical application of the method is verified by the prediction and comparative analysis of measured settlements based on engineering examples. The result of research shows that the method can predict the foundation settlement after loading during construction of engineering fill. This method has obvious advantages over the traditional curve fitting method and can guide the actual engineering construction.

Keywords: parameter inversion, settlement prediction, soft soil subgrade

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1. Introduction

The settlement and deformation characteristics of highway soft soil subgrade under loading have been paid much attention [1]. During the construction of railways and highways in the areas of soft soil, the settlement of soft soil roadbed is one of the biggest problems. Many of the engineering accidents are triggered by the excessive settlement of soft soil subgrades [2]. Moreover, long-term traffic loads can lead to settlement of transport infrastructure on soft soil subgrade, so predicting settlement is of great importance in engineering design [3]. Soft soil has the characteristics of high water content, large porosity, low shear strength and permeability, high compressibility and sensitivity [4, 5]. Under the action of external loading, it is characterized by low bearing capacity, large uneven deformation, long deformation stabilization time [6–9],etc., which can easily cause roadbed instability and excessive post-construction settlement. This is due to the infiltration of rainwater into the soil medium and the increase in soil water content. The movement of water causes the soil skeleton to collapse and settlement [10]. Post-construction settlement is easy to cause pavement cracking, pavement sag, "bumping at bridgehead" and other undesirable phenomena. It greatly affects the comfort and safety of driving and reduces the road usage quality. Consequently, in order to ensure that the roadbed settlement to meet the requirements of use, reasonable arrangement of embankment filling rate and preloading time, it is necessary to accurately calculate and predict the settlement of soft foundation. Accurate and timely settlement prediction can provide some guidance for reasonable planning of construction progress, determining pavement paving time, scientifically arranging the height of subgrade layering filling, intermittent time and preloading time. It can shorten the construction period and improve the construction efficiency [11].

At present, based on the measured settlement information on site, the method of predicting the development law of settlement and projecting the settlement in the later stage has become one of the main directions of the subgrade settlement prediction research. Settlement prediction methods based on measured data can be roughly divided into three categories. The first is the curve fitting method. This type of method is generally used to fit the development law of settlement with a simple function. Some of the methods have a certain theoretical basis, such as the Asaoka method [12, 13], exponential curve method [14], Hushino method and growth curve method. But some of them mainly use mathematical formulas to make a simple fit for the settlement of foundations, such as hyperbolic method [15], etc. The second is the systematic theoretical methods, such as time series method, grey theory method, and neural network method. The third is the numerical analysis method. This kind of method generally adopts the finite element method, which firstly inverts the calculated parameters and then positively predicts the later settlement. Because the engineering mechanical properties of foundation is a process of gradual change with loading, and the embankment load is actually applied step by step. Its settlement is the result of the combined effect of many factors such as filling process, filling load [16], etc. The prediction of foundation settlement under the comprehensive consideration of graded loading is more reflective of the deformation trend of foundation. However, the above methods are generally only applicable to the prediction of settlement under the current level of loading. This leads that the settlement prediction problems cannot be solved well, such as the design of preloading schemes and the calculation of presetting height. Consequently, it is of great engineering significance to propose a simple calculation and accurate prediction method, which is able to predict settlement better.

In this article, in view of the inadequacy of the existing settlement prediction methods, based on the improved Shunsuke Takagi method, we propose a method that can predict settlement better. And relying on the settlement monitoring data of the typical soft foundation section of Zhaoyang West Ring Expressway in Zhaotong City, Yunnan Province, we analyze deeply the practical application effect of the prediction method by comparing it with the measured data. Meanwhile, we validate the validity of the model by comparing it with the curve-fitting prediction method, the Hushino method and the measured information.

2. Inversing calculation method of soft soil ground consolidation parameters during graded loading

2.1. Solving the average degree of consolidation based on the improved Shunsuke Takagi method

Expressway roadbed filling is loaded step by step. A large number of projects have shown that the improved Shunsuke Takagi method for calculating the degree of consolidation under the condition of step-by-step loading is more in line with the actual situation.

The theoretical solution is proposed by Shunsuke Takagi for the degree of consolidation under arbitrary variable speed loading [20].

When $0 < t < T$, the degree of consolidation for p is as follows:

$$\overline{W_t} = \frac{1}{p}\int_0^t \overline{W}_{(t-\tau)}\dot{q}_\tau d\tau \tag{2.1}$$

When $t > T$, the degree of consolidation for $\bar{p}$ is as follows:

$$\overline{W_t} = \frac{1}{\bar{p}}\int_0^T \overline{W}_{(t-\tau)}\dot{q}_\tau d\tau \tag{2.2}$$

where: $\overline{W}_{(t-\tau)}$ – theoretical solution for instantaneous loading consolidation, τ – arbitrary loading time, $\dot{q}_\tau$ – rate of loading at τ, T – loading terminal time, p – sum of load increments up to moment t

Shunsuke Takagi's formula only considers radial drainage consolidation, ignoring vertical drainage consolidation. Zeng [21] improved Shunsuke Takagi method by considering the vertical drainage degree of consolidation, combining both radial and vertical drainage degrees of consolidation. The theoretical solution for the degree of consolidation is expressed in an ordinary formula:

$$\overline{W} = 1 - ae^{-bt} \tag{2.3}$$

Replace $\overline{W}_{(t-\tau)}$ in Eq. (2.1) and (2.2) with the ordinary Eq. (2.3), and then integrate to obtain the average degree of consolidation of foundation at the time t under multi-stage constant velocity loads. In other words, the general formula for calculating the average degree of consolidation of foundation with the improved Shunsuke Takagi method is as follows:

$$\overline{W_t} = \sum_{i=1}^{n} \frac{\dot{q}_i}{\sum \Delta p} \left[T_i - T_{i-1} - \frac{a}{b} e^{-bt} \left(e^{bT_i} - e^{bT_{i-1}}\right)\right] \tag{2.4}$$

where: $\overline{W_t}$ – average degree of consolidation corrected for multistage equal velocity loading at moment t, $\dot{q}_i$ – loading rate for load level i, $\sum \Delta p$ – the cumulative value of each level of load, T_i – the start times of the loading of level i, T_{i-1} – the end times of the loading of level i, When calculating the degree of consolidation at some time t during the loading of level i, T_i is changed to t. $a = \dfrac{8}{\pi^2}$, $b = \dfrac{\pi^2 C_V}{4L^2}$. C_V – consolidation coefficient, L – Soil thickness, Let $T_i - T_{i-1} = \Delta T$, $e^{bT_i} - e^{bT_{i-1}} = C$, which simplifies to:

$$\overline{W_t} = \sum_{i=1}^{n} \frac{\dot{q}_i}{\sum \Delta p} \left[\Delta T - \frac{a}{b} C e^{-bt}\right] \tag{2.5}$$

2.2. Inverse calculation of consolidation parameters

The solution of consolidation parameters is a crucial link in the settlement prediction of soft soil subgrade under graded loading. The principle of exponential curve method is used to calculate the consolidation parameter b value. The theoretical solution of the average consolidation degree of soil layer can be summarized as follows:

$$W = 1 - ae^{-bt} \tag{2.6}$$

where: W – the degree of consolidation under instantaneous loading conditions

Three points are selected from the time-settlement curve of the measured value, namely (t_1, S_1), (t_2, S_2) and (t_3, S_3), and the time interval of three points is required to be equal, as follows:

$$t_2 - t_1 = t_3 - t_2 \tag{2.7}$$

At the above three moments, the degree of consolidation of soil layer corresponding to each moment can be obtained as follows:

$$W_1 = 1 - ae^{-bt_1} \tag{2.8}$$

$$W_2 = 1 - ae^{-bt_2} \tag{2.9}$$

$$W_3 = 1 - ae^{-bt_3} \tag{2.10}$$

Associative Eq. (2.8), (2.9) and (2.10), after collation it can be obtained:

$$b(t_2 - t_1) = \ln\left(\frac{1 - W_1}{1 - W_2}\right) \tag{2.11}$$

$$b(t_3 - t_2) = \ln\left(\frac{1 - W_2}{1 - W_3}\right) \tag{2.12}$$

The degree of consolidation is defined as:

$$W = \frac{S_t - S_d}{S_u - S_d} \tag{2.13}$$

where: S_d – the immediate settlement, S_u – the final settlement

The calculation formula of consolidation parameters b can be obtained from Eq. (2.11), (2.12) and (2.13):

$$b = \frac{1}{(t_2 - t_1)} \ln\left(\frac{S_2 - S_1}{S_3 - S_2}\right) \tag{2.14}$$

where: S_1, S_2, S_3 – the settlement values corresponding to the three moments t_1, t_2, and t_3, respectively

The value of consolidation parameter is the key to calculate the degree of consolidation at different time. The value of consolidation parameters in the traditional modified Shunsuke Takagi method is controversial to some extent, because in reality the soil consolidation parameters are constantly changing. However, both the three-point method and the improved Shunsuke Takagi method are proposed based on one-dimensional consolidation theory [17, 18]. In both approaches, the physical meaning of b is identical. Moreover, the process of inverse calculation of consolidation parameters by the exponential curve method is very simple, and it is widely used in engineering. Therefore, the consolidation parameters obtained by the inverse calculation of the exponential curve method are used as the consolidation parameters substituted by the improved Shunsuke Takagi method in this article.

3. The method that is able to predict soft soil subgrade settlement better

3.1. Settlement formula based on graded loading

According to the improved Shunsuke Takagi method, under the action of the first n loads, the degree of consolidation of foundation at t_1 and t_2 is as follows:

$$W_{t_1 p_i} = \sum_{i=1}^{n} \frac{\dot{q}_i}{\sum \Delta p}\left[\Delta T - \frac{a}{b} C e^{-bt_1}\right] \tag{3.1}$$

$$W_{t_2 p_i} = \sum_{i=1}^{n} \frac{\dot{q}_i}{\sum \Delta p}\left[\Delta T - \frac{a}{b} C e^{-bt_2}\right] \tag{3.2}$$

In the formula, ΔT and C are the same as above.

The settlement of subgrade during the roadbed filling mainly includes immediate settlement and primary consolidation settlement [19], then the settlement at the moment of t_1 and t_2 are as follows, respectively:

$$S_{t_1} = S_d + S_{cp} W_{t_1 p_i} \tag{3.3}$$

$$S_{t_2} = S_d + S_{cp} W_{t_2 p_i} \tag{3.4}$$

where: S_d – the immediate settlement, S_{cp} – the total consolidation settlement, $W_{t_1 p_i}$ and $W_{t_2 p_i}$ – the degree of consolidation of foundation at t_1 and t_2

Eq. (3.1) and (3.2) are substituted into Eq. (3.3) and (3.4) respectively, and Eq. (3.3) is subtracted from Eq. (3.4). In this way, the immediate settlement can be eliminated and the settlement difference expression at different times can be obtained. The solution process is as follows:

$$S_{t_1} = S_d + S_{cp} \sum_{i=1}^{n} \frac{\dot{q}_i}{\sum \Delta p} \left[\Delta T - \frac{a}{b} C e^{-bt_1} \right] \tag{3.5}$$

$$S_{t_2} = S_d + S_{cp} \sum_{i=1}^{n} \frac{\dot{q}_i}{\sum \Delta p} \left[\Delta T - \frac{a}{b} C e^{-bt_2} \right] \tag{3.6}$$

$$\sum_{i=1}^{n} \frac{\dot{q}_i}{\sum \Delta p} \left[\Delta T - \frac{a}{b} C e^{-bt_2} \right] - \sum_{i=1}^{n} \frac{\dot{q}_i}{\sum \Delta p} \left[\Delta T - \frac{a}{b} C e^{-bt_1} \right] = \frac{S_{t_2} - S_{t_1}}{S_{cp}} \tag{3.7}$$

$$S_{cp} = \frac{S_{t_2} - S_{t_1}}{\sum_{i=1}^{n} \frac{\dot{q}_i}{\sum \Delta p} \left[\Delta T - \frac{a}{b} C e^{-bt_2} \right] - \sum_{i=1}^{n} \frac{\dot{q}_i}{\sum \Delta p} \left[\Delta T - \frac{a}{b} C e^{-bt_1} \right]} \tag{3.8}$$

Further simplification of Eq. (3.8) gives the equation for final consolidation settlement.

$$S_{cp} = \frac{S_{t_2} - S_{t_1}}{\frac{a}{b} \left(e^{-bt_1} - e^{-bt_2} \right) \sum_{i=1}^{n} \frac{C \dot{q}_i}{\sum \Delta p}} \tag{3.9}$$

The total consolidation settlement is actually a constant value. Thus, t_2 can be set as a steady state value, and t_1 can be used as an independent variable to fit a horizontal line. The corresponding ordinate value is the completed value of the primary consolidation settlement. It can also be seen from Eq. (3.9) that the final primary consolidation settlement increases with the increase of the total design loading. The above method is similar to the traditional exponential curve method, but unlike the exponential curve method, this method can take into account the effects of the loading process.

The essence of the above fitting method for solving total consolidation settlement is to take a fixed b value, and different b values lead to different consolidation degrees at different times. Actually, soil parameters are constantly changing along with the filling process. Therefore, the total consolidation settlement obtained through reverse calculation is different from the practical total settlement. But, it is found that different b values have little influence on the predicted results of total settlement according to the actual calculation and comparison.

3.2. Prediction formula of settlement

After calculating b and S_{cp} in the above manner, the settlement value can be calculated as follows:

1. Under equal loading
   According to the previous process, when there is no change in loading, the measured settlement value at t_0 is s_0, then the settlement value at any moment t after t_0 is as follows:

$$S_t = S_{t_0} + \frac{a}{b} S_{cp} \left[\sum_{i=1}^{n} \frac{C\dot{q}_i}{\sum \Delta p} \left(e^{-bt_1} - e^{-bt_2} \right) \right] \tag{3.10}$$

   where: S_{t_0} – the settlement value of the predicted starting point

2. Under subsequent loading
   In the case of subsequent continuation of load application, ignoring the effect of transient settlement, the sedimentation value of the subgrade at different moments can be expressed as:

$$S_{t_0} = S_d + S_{cp} \sum_{i=1}^{n} \frac{\dot{q}_i}{\sum \Delta p} \left[\Delta T - \frac{a}{b} C e^{-bt_0} \right] \tag{3.11}$$

$$S_t = S_d + S_{cp} \sum_{i=1}^{n+k} \frac{\dot{q}_i}{\sum \Delta p} \left[\Delta T - \frac{a}{b} C e^{-bt} \right] \tag{3.12}$$

By associating Eq. (3.7) and (3.8), the settlement value of the roadbed at arbitrary moment can be obtained as:

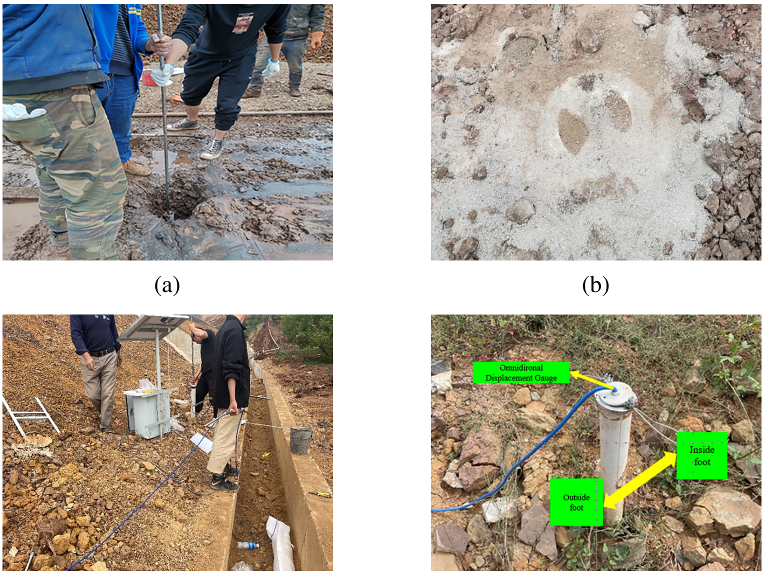
$$S_t = S_{t_0} + \frac{a}{b} S_{cp} \left[\sum_{i=1}^{n} \frac{C\dot{q}_i}{\sum \Delta p} \left(e^{-bt_1} - e^{-bt_2} \right) \right] + S_{cp} \sum_{i=n+1}^{n+k} \frac{\dot{q}_i}{\sum \Delta p} \left[\Delta T - \frac{a}{b} C e^{-bt_2} \right] \tag{3.13}$$

where: k – the subsequent loading series

4. Engineering example verification

4.1. Site overview

Based on the Zhaotong West Ring Highway project in Zhaoyang, Yunnan Province, this paper conducts research to verify the effectiveness of this method. In this project, the deformation of high fill subgrade on the high-speed soft soil foundation is observed by embedding single-point settlement meter, omnidirectional displacement meter and other displacement monitoring elements. The monitoring data is read in real time and transmitted remotely by establishing observation base stations. The actual monitoring information can effectively judge the working state of the subgrade, find the danger in the project in time, analyze and calculate the settlement of the roadbed. These will provide the engineering basis for subsequent roadbed filling and settlement control. It is of great significance to ensure the quality and safety of the project. Part of the process of the layout of each monitoring element is shown in Fig. 1 below.



(a) (b) (c) (d)

Fig. 1. Layout of monitoring elements: a) Buried completed single-point settlement meter, b) Buried completed settlement meter, c) Vertical omnidirectional displacement gauge, d) Completed inclinometer installation

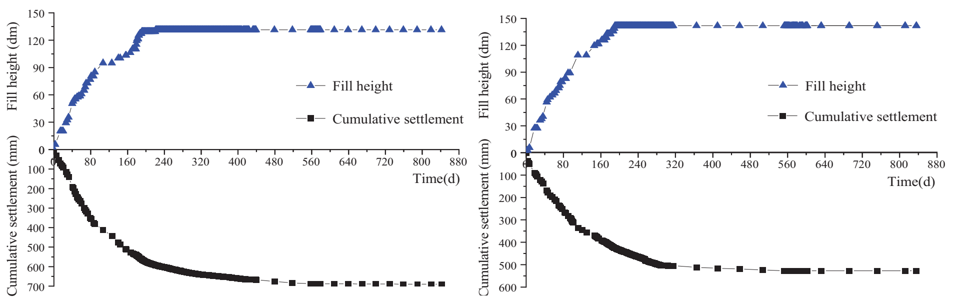
Data acquisition is done by establishing a base station on the spot, which is fixed using concrete at the bottom. The base station is powered by solar panels absorbing solar energy. The collected power is stored in a battery. Meanwhile, the data is transmitted wirelessly using a DTU. The observation base station and internal components are shown in Fig. 2.

(a) (b)

Fig. 2. Base station diagram: a) Installed base station b) Internal structure

4.2. Soft soil subgrade settlement monitoring

In order to provide data support to verify the method, this article relies on the Zhaoyang West Ring Highway project in Yunnan province to carry out research. The monitoring point of the project is located in the range of soft soil roadbed. The foundation condition is poor and the filling height is high. So it is necessary to conduct settlement observation on the high-fill section on the soft soil foundation during construction. Based on the measured settlement data, the subsequent settlement amount of the embankment is predicted and the state of the embankment is judged, so as to ensure the construction quality of the embankment. The single-point settlement meter is one of the most widely used settlement monitoring equipment at present. The settlement value of the subgrade is measured by the single-point settlement meter on site. In order to ensure the reliability of the monitoring data, the burying scheme should be adjusted according to the actual situation on site. The single-point settlement meter is combined with the acquisition module and the wireless transceiver module. It realizes the wireless collection and transmission of settlement data, and obtains the time ~filling height ~settlement curve (T~H~S) of the full filling process. The on-site settlement curve is shown in Fig. 3.



(a) (b)

Fig. 3. Fill-settlement curve graph: a) Settlement curve of K5+810 section, b) Settlement curve of K5+900 section

The settlement curve from Fig. 3 has the following characteristics: (1) The foundation of this section bears a large load and takes a long time to fill, and the phenomenon of rapid filling occurred due to the requirements of construction schedule. (2) In the early stage of embankment filling, the overlying load gradually increases with the increasing of the filling height, and the settlement of the roadbed develops rapidly. Comparing the settlement change amount before and after the embankment filling, the settlement change amount of the roadbed was significantly reduced under the same load change amount. This indicates that the soil consolidation occurs simultaneously during the filling and loading period, and the strength of the soil body increases gradually. (3) In the later stage of embankment filling, after the filling height is not increased, the settlement of the roadbed gradually tends to be gentle until stable. It indicates that the roadbed settlement is complete.

4.3. Calculation and analysis of consolidation parameters

Firstly, the b value of foundation soil is calculated backwards according to equation (2.14). When selecting data points for calculation, multiple points should be selected as far as possible for multiple calculations, and the average value is taken. The calculated result is that the b value is equal to 0.0108d^{-1}.

Further, the total consolidation settlement was obtained according to Eq. (3.9), and the least square method was used to fit the data. Equation (3.9) is derived on the premise that there is no loading between t_1 and t_2, and the longer the time separates, the better the effect will be. Therefore, the data of 245–255 days is used as t_1, and the data of 262 days is used as t_2 to fit a total of 11 days of data, as shown in Fig. 4. The total consolidation settlement value S_{cp} obtained from the fit is 211.0268 mm.

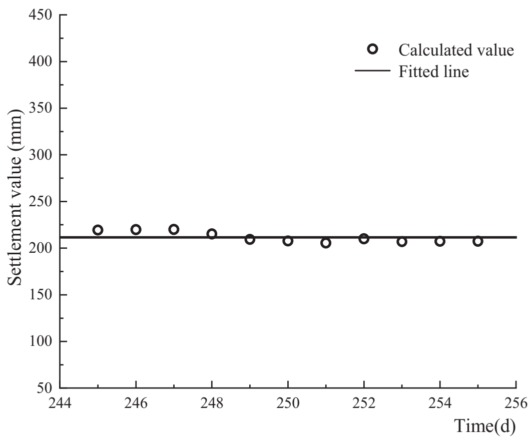


Fig. 4. Fitting diagram

By changing the b value, we can explore whether different final primary consolidation settlement values will affect the prediction of residual settlement. The calculation results are shown in Fig. 5. It can be seen from the figure that although the final primary consolidation settlement values obtained by fitting under different b values differ greatly, and the maximum difference can reach 500 mm. In comparison, the predicted total settlement value obtained by considering only the primary consolidation settlement has little difference, the maximum is about 10 mm. The reason is that when the b value is larger, the final primary consolidation settlement obtained by fitting is larger, but the corresponding consolidation degree is also larger. Both of them are obtained by fitting the formula that produces the same settlement difference in the same time, and the settlement basically converges in the later stage of construction. Therefore, the final residual settlement between the two is not very different. In summary, the difference of the final primary consolidation settlement value obtained by different b values has little influence on the accuracy of prediction.

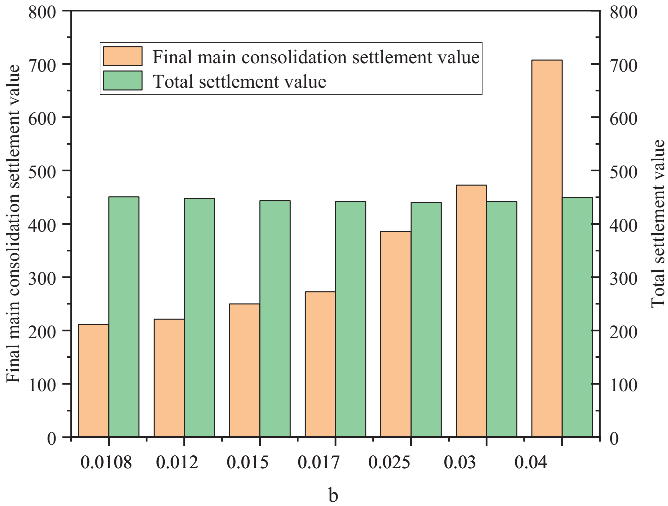


Fig. 5. Total settlement values for different b

4.4. Comparison of the effectiveness of forecasting methods

After obtaining the values of b and a through the above process, the predicted settlement profiles are obtained by substituting them in Eq. (3.11) and (3.13). Hyperbolic method and Hushino method are used to make prediction. Compared with this method, the effectiveness of this method is verified. Figure 6a shows the fitting effect diagram of hyperbolic method, with R^2 reaching 0.98, indicating good data fitting effect. Figure 6b shows the comparison between the proposed method, hyperbolic method and Hushino method. It can be seen from the figure that the overall prediction effect of the proposed method is better than that of the hyperbolic method and Hushino method, which is close to the actual monitoring data. The

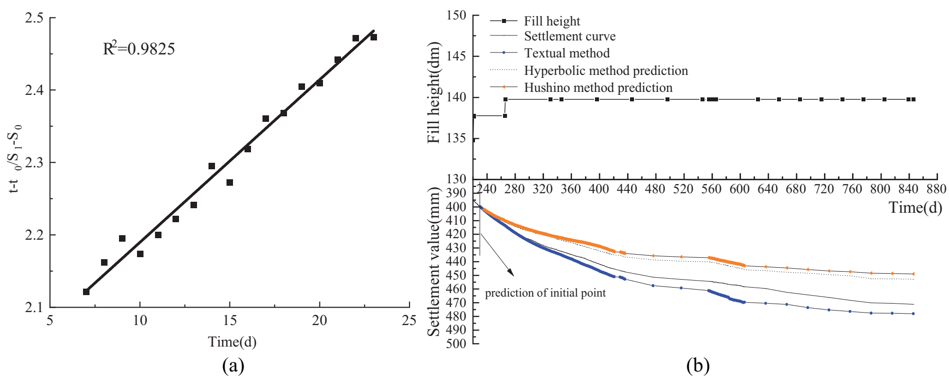


Fig. 6. Settlement prediction diagram: a) Hyperbolic method fitting effect, b) Comparison of this paper with hyperbolic method and the Hushino method

prediction effect of the hyperbolic method and Hushino method is similar. Moreover, the prediction effect is better in the early stage, but after loading, the predicted value is small. This is because with the increase of the subgrade load, the settlement will also develop accordingly, and the parameters based on the fitting of the previous grade load cannot reflect this changing process. As a result, the error will gradually increase with the development of time. In conclusion, the feasibility and effectiveness of the proposed method are verified.

5. Conclusions

In order to comprehensively consider the settlement monitoring data of graded loading and better reflect the deformation trend of soft ground, the measured settlement data of Yunnan Zhaoyang West Ring Expressway Project is taken as the basis. Based on the improved Shunsuke Takagi method for calculating the degree of foundation consolidation, a new method which can predict settlement is proposed better. It can predict the settlement of foundation under the action of the next load according to the observed settlement of foundation under the action of the previous load. The following conclusions can be drawn from the study in this paper:

1. In this paper, a new method is proposed that can realize the prediction of settlement better. This method obtains the required calculation parameters through the measured settlement data of different filling intermittent periods. The calculation process is simple and can predict the settlement change under the action of the next load better, which is more accurate than the traditional prediction method.
2. Because the change of calculation parameters is not considered, there may be a certain difference between the total consolidation settlement obtained by reverse calculation and the actual value. Through practical calculation, it is found that although the total consolidation settlement value obtained by reverse calculation under different b values is quite different, it has little impact on the calculation of residual settlement and final settlement.
3. The new method proposed in this paper is compared and analyzed with the hyperbolic method and the Hushino method as well as the measured settlement data, and it is concluded that the method is closer to the actual measured data. The validity of the method is verified.

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References

[1] L. Zheng, F. Ran, C. Lihao, S. Jianbo, and X. Shaohua, "Long-term deformation of highway subgrade under coupling effect of traffic load and drying-wetting cycles", *International Journal of Geomechanics*, vol. 20, no. 2, 2020, doi: 10.1061/(ASCE)GM.1943-5622.0001568.

[2] M. Nadeem, M. Akbar, P. Huali, L. Xiaoqing, O. Guoqiang, and A. Amin, “Investigation of the settlement prediction in soft soil by Richards Model: based on a linear least squares-iteration method”, *Archives of Civil Engineering*, vol. 67, no. 2, pp. 491–506, 2021, doi: 10.24425/ace.2021.137181.

[3] W. Tingyu, J. Hongxu, G. Lin, S. Honglei, T. Junhao, J. Yaochen, and W. Pengfei, “Predicting method on settlement of soft subgrade soil caused by traffic loading involving principal stress rotation and loading frequency”, *Soil Dynamics and Earthquake Engineering*, vol. 152, art. no. 107023, 2022, doi: 10.1016/j.soildyn.2021.107023.

[4] X. Junhua, S. Jie, W. Nan, L. Mengbo, W. Hongyu, S. Siqi, and L. Xuyou, “Long-term settlement of metro viaduct piers: a case study in Shanghai soft soil”, *Transportation Geotechnics*, vol. 42, art. no. 101075, 2023, doi: 10.1016/j.trgeo.2023.101075.

[5] F. Shuangxi and L. Huayang, “A settlement prediction model considering tidal loading and traffic loading of soft soil subgrade”, *Computers and Geotechnics*, vol. 144, art. no. 104639, 2022, doi: 10.1016/j.compgeo.2022.104639.

[6] M. Esmaeili and H. Khajehei, “Mechanical behavior of embankments overlying on loose subgrade stabilized by deep mixed columns”, *Journal of Rock Mechanics and Geotechnical Engineering*, vol. 8, no. 5, pp. 651–659, 2016, doi: 10.1016/j.jrmge.2016.02.006.

[7] S. S. Roy and K. Deb, “Bearing capacity of rectangular footings on multilayer geosynthetic-reinforced granular fill over soft soil”, *International Journal of Geomechanics*, vol. 17, no. 9, 2017, doi: 10.1061/(ASCE)GM.1943-5622.0000959.

[8] N. Jing, I. Buddhima, G. Xueyu, at al., “Model of soft soils under cyclic loading”, *International Journal of Geomechanics*, vol. 15, no. 4, art. no. 04014067, 2015, doi: 10.1061/(ASCE)GM.1943-5622.0000411.

[9] Z. D. Cui and S. X. Ren, “Prediction of long-term settlements of subway tunnel in the soft soil area”, *Natural Hazards*, vol. 74, no. 2, pp. 1007–1020, 2014, doi: 10.1007/s11069-014-1228-y.

[10] P. Popielski, B. Bednarz, T. Majewski, and M. Niedostatkiewicz, “Settlement of a historic building due to seepage-induced soil deformation”, *Archives of Civil Engineering*, vol. 69, no. 2, pp. 65–82, 2023, doi: 10.24425/ace.2023.145253.

[11] X. Geng and H. S. Yu, “A large-strain radial consolidation theory for soft clays improved by vertical drains”, *Geotechnique*, vol. 67, no. 11, pp. 1020–1028, 2017, doi: 10.1680/jgeot.15.T.013.

[12] L. Chunlin, “A simplified method for prediction of embankment settlement in clays”, *Journal of Rock Mechanics and Geotechnical Engineering*, vol. 6, no. 1, pp. 61–66, 2014, doi: 10.1016/j.jrmge.2013.12.002.

[13] S.-A. Tan and S.-H. Chew, “Comparison of the hyperbolic and ASAOKA observational method of monitoring consolidation with vertical drains”, *Soils and Foundations*, vol. 36, no. 3, pp. 31–42, 1996, doi: 10.3208/sandf.36.3_31.

[14] S. G. Chung and H. J. Kweon, “Prediction of radial consolidation settlement with consideration of sampling range effect: Updated observational methods”, *Journal of Geotechnical and Geoenvironmental Engineering*, vol. 147, no. 12, 2021, doi: 10.1061/(ASCE)GT.1943-5606.0002704.

[15] M. A. Al-Shamrani, “Applying the hyperbolic method and Ca/Cc concept for settlement prediction of complex organic-rich soil formations”, *Engineering Geology*, vol. 77, no. 1-2, pp. 17–34, 2005, doi: 10.1016/j.enggeo.2004.07.004.

[16] Z. Caihui and L. Ning, “Ranking of influence factors and control technologies for the post-construction settlement of loess high-filling embankments”, *Computers and Geotechnics*, vol. 118, art. no. 103320, 2020, doi: 10.1016/j.compgeo.2019.103320.

[17] D. G. Fredlund and J. U. Hasan, “One-dimensional consolidation theory: unsaturated soils”, *Canadian Geotechnical Journal*, vol. 16, no. 3, pp. 521–531, 1979, doi: 10.1139/t79-058.

[18] L. Julie, R. Wayne, and S. Nagaratnam, “Consolidation behavior of soils subjected to asymmetric initial excess pore pressure distributions”, *International Journal of Geomechanics*, vol. 10, no. 5, pp. 181–189, 2010, doi: 10.1061/(ASCE)GM.1943-5622.0000061.

[19] K. C. Foye, P. Basu, and M. Prezzi, “Immediate settlement of shallow foundations bearing on clay”, *International Journal of Geomechanics*, vol. 8, no. 5, pp. 300–310, 2008, doi: 10.1061/(ASCE)1532-3641(2008)8:5(300).

[20] Z. Changsheng, G. Mingxian, and Z. Xiaojun, "Variation laws of consolidation coefficent of marine clay in Houhai Bay of Shenzhen", *Chinese Journal of Geotechnical Engineering*, vol. 35, no. A1, pp. 247–252, 2013.

[21] G. Qinghua, "The Study of Settlement Calculation and Consolidation Characteristic for Vacuum Combined with Surcharge Preloading", M.Eng. thesis, Hohai University, China, 2007.

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