Settlement prediction of embankments with stage construction on soft ground

软土地基上分期施工的路堤沉降预测方法

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Abstract: The magnitude and rate of the settlement are the key elements subjected to design analysis of embankments on soft ground. The observational methods based on field measurement have indicated the promising results and become effective methods to predict the final settlement, while the uncertainties of parameters and theories limit significantly the accuracy of settlement estimation. This paper presents an observational method to predict the settlement performance of embankments with stage construction on soft ground based on Asaoka method. The case studies show the accordance of the predicting results with the field measured data. It is also given from the case study that the value of E_u/c_u ratio ranges from 50 to 100 for Jiangsu Marine clay and its actual coefficient of consolidation is almost one order of magnitude larger than the laboratory data.

Key words: settlement; embankment; observational method; stage construction; Jiangsu Marine clay
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摘 要: 沉降量和沉降速率控制是软土地基上路堤工程设计的关键问题,由于固结理论的局限性和参数的不确定性,理论预测的精度较低,而基于现场实测数据的观测法显示出较高的精度.本文在 Asaoka 观测法的基础上,发展了一种软土路基上分期施工时路堤沉降预测的方法,结合江苏海相软土上的高速公路工程进行了沉降预测分析.

关键词: 沉降; 路堤; 观测法; 分期施工; 江苏海相软土

0 Introduction①

Settlement and stability are two primary considerations systematically related to the design of an embankment on soft ground. The tools available for the stability evaluation seem to be satisfactory. The key element of long term behavior of the embankment routinely subjected to design analysis is the settlement[1]. In other words, the settlement analysis is the most appropriate approach to the embankment analysis.

The settlements of embankments on soft clays result from the consolidation and the lateral flow under the embankments. Many researches have been made on performance of embankments on soft ground[1~8].

Although many experiences have shown the practical value of the theory for estimating settlements and settlements rates, they also illustrated some of the problems involved in making accurate prediction of the settlement. Duncan(1993) and Olson(1998) analyzed the uncertainties causing the shortcomings in the current state of the art for settlement prediction respectively[6,9]. These uncertainties sometimes make it difficulty or impossible to estimate the magnitude and rate of settlement for embankments. Although the numerical analysis may be possible to improve the accuracy, the soil models may involve many parameters that can not be determined economically. However, the evolution of numerical methods with computer may result in simpler models and complete codes that are increasingly becoming available.

It is desirable therefore to develop observational methods based upon which the settlement can be estimated once sufficient data has been recorded. Many researchers developed the settlement prediction methods on field measurement observation, which have indicated promising results and become an accepted method to estimate final settlements and rates of settlements[10~16].

Stage construction is a typical procedure for embankments on the soft ground. With a certain period of consolidation at every stage construction, the safety factor of the embankment can be generally raised and the post construction settlement may be reduced. The settlement-time curve during stage construction may be more complicated than it is with instantaneous loading. The period for primary consolidation at a definite final load with stage construction may be increased significantly, in spite of the fact that the post construction settlement can be reduced[17~19]. In order to speed up the rate of settlement and minimize the post construction secondary settlement of soft clays, surcharge is often used in practice, which can be taken as a type of stage construction with temporary loading and unloading stages.

Problems related to the settlement analysis of stage construction for embankments on soft clays are of the following types:

(1) Prediction of the deformation behavior of stage construction from the results of borings and tests.

(2) Prediction of the final settlement at permanent load from the behavior of the first stage construction.

(3) Prediction of the post construction settlement at the permanent load and corresponding time of surcharge removed from the behavior of the surcharge.

The first of these problems is heavily dependent on the theory, which is necessary in design. The other two pre-

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dictions require empirical rather than theoretical methods because they are based on observational data. In any case, the fact that the second and third predictions are derived from field observations makes them more reliable than the theoretical predictions.

Leroueil et al revealed the effective stress path and analyzed the relationship between vertical settlement and lateral displacement during stage construction[2,20]. Stamatopoulos and Kotzias developed a method to determine the final settlement at permanent load from the behavior of surcharge[12,13], but it is based on the elastic theory and difficult to calculate the rate of the settlement. The hyperbolic method is based on the total load- settlement relationship to predict the final settlement, which is not sensitive to the nature of the initial loading condition[15].

This paper presented a method for the prediction of the final settlement at permanent load from the behavior of the first stage construction based on the Asaoka method.

1 Stage observational method

Asaoka proposed an 'observational procedure' to estimate the final settlement and in-situ coefficient of consolidation from the field observational data (Fig. 1)[10]. This method is becoming increasing popular because of its simplicity and effectivity.

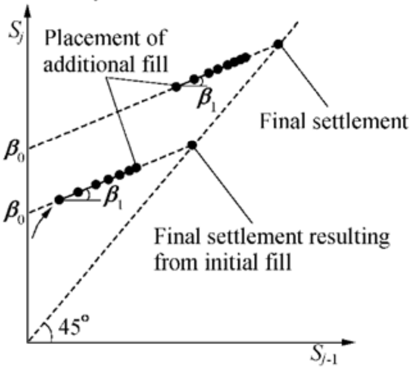


Fig. 1 The Asaoka method

The method is based on the fact that one dimensional consolidation settlements $S_0, S_1, S_2, \cdots, S_j$ at times $0, \Delta t, 2\Delta t, \cdots, j\Delta t$ can be expressed as a first order approximation by

$$S_j = \beta_0 + \beta_1 S_{j-1}, \tag{1}$$

which represents a straight line in a S_j vs S_{j-1} plot (Fig. 1), where β_0 is the intercept and β_1 is the slope of the line. When the ultimate settlement has been reached: $S_j = S_{j-1} = S_f$, therefore, the ultimate settlement S_f can be given by

$$S_f = \frac{\beta_0}{1-\beta_1} \tag{2}$$

and

$$\ln\beta_1 = -\frac{6C_v\Delta t}{H^2}(\text{both top and bottom drainage}), \tag{3}$$

$$\ln\beta_1 = -\frac{2C_v\Delta t}{H^2}\quad(\text{top drainage}). \tag{4}$$

The constant β_1 has been suggested by Magnan and Deroy to be related to the coefficient of consolidation C_v as follows[22]: for horizontal radial drainage only

$$C_h = \frac{-D_e^2F}{8}\cdot\frac{\ln\beta_1}{\Delta t}, \tag{5}$$

for vertical drainage only

$$C_v = \frac{-5H^2}{12}\cdot\frac{\ln\beta_1}{\Delta t}, \tag{6}$$

where D_e, H are the drainage path length respectively.

Asaoka method also stated that the straight line in S_j - S_{j-1} space would moved up in the case of multi-staged loading (Fig. 1), moreover, the shifted lines become almost parallel to the initial when the settlement is relatively small compared to the thickness of clay layer. However, it is not discussed and provided how to determine the shift distance from the line of first stage to the line of the next stage.

In the expression (1), when $j = 0$ that is: $t = 0$ and $S_{(t=0)} = S_0$, where t can be taken as 0 from any time after loading works. If t is set as 0 at the exact time once the load is exerted, then, S_{j-1} becomes 0, therefore,

$$S_0 = \beta_0 = \text{immediate settlement } S_e. \tag{7}$$

This means that Asaoka method can be extended to obtain the construction settlement, which equals to the intercept β_0 of the liner line in the space S_j, S_{j-1}, where $t = 0$ is set just after loading. Moreover, this immediate settlement contributes the shift distance of the parallel lines during stage construction.

In fact, from the derivation of the Asaoka method, the settlement of soil layers can be expressed as

$$S_t = \int_0^H \varepsilon(t,z)\,\mathrm{d}z \tag{8}$$

and

$$\varepsilon(z,t) = T + \frac{1}{2!}\left(\frac{Z^2}{C_v}\dot{T}\right) + \frac{1}{4!}\left(\frac{Z^4}{C_v^2}\ddot{T}\right) + \cdots + ZF + \frac{1}{3!}\left(\frac{Z^3}{C_v}\dot{F}\right) + \frac{1}{5!}\left(\frac{Z^4}{C_v^2}\ddot{F}\right) + \cdots, \tag{9}$$

where T and F are two unknown function of time.

With the vertical drainage boundary conditions and at the ground surface, $\varepsilon(t,z) = T = \varepsilon_{(t,z=0)}$. If $t = 0$, $\varepsilon(t,z) = \varepsilon_{(t=0,z=0)} = \varepsilon_e$ = initial elastic strain. Therefore, $S(t=0) = S_0$ gives the immediate settlement S_e, which can also be estimated from the elastic method by the equation:

$$S_0 = S_e = \frac{(1-\nu^2)qbI}{E_u}. \tag{10}$$

It is clearly shown that the Asaoka method has been extended to predict the settlement of embankments with stage construction. In other words, the behavior of next stage construction can be predicted with the β_0, β_1 from the last stage construction. The more the previous stages with settlement measurement, the higher the accuracy of next stage prediction. The stage observational method includes following steps:

(1) Sketch observed time settlement curve.

(2) Choose a time interval Δt, which usually ranges from 10 to 100 days, read the settlements S_j from the curve at times $t_j (= \Delta t_j, j = 1, 2, 3, \cdots)$.

(3) Plot the settlements S_j, S_{j-1} in a coordinate system with axis S_j, S_{j-1} originated from 0.

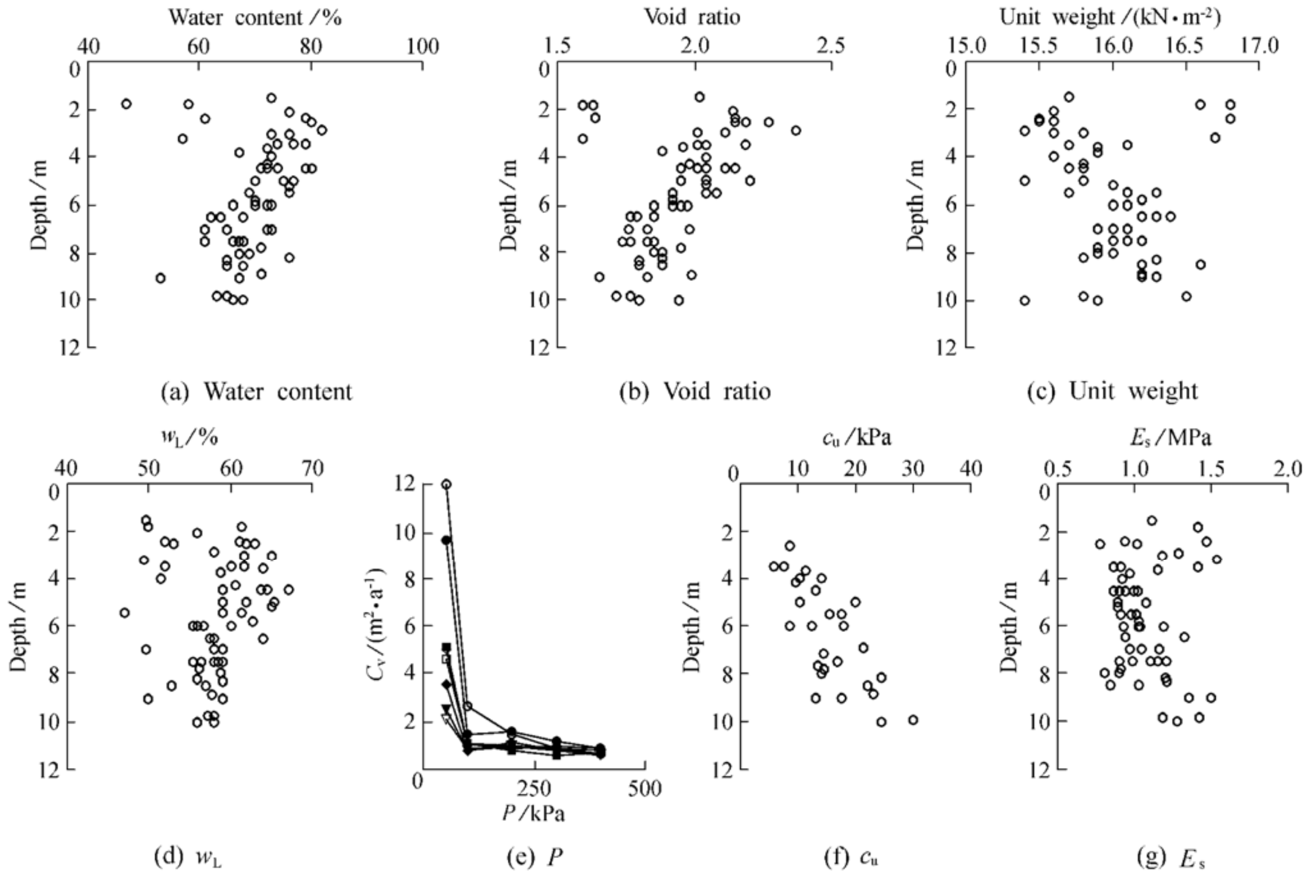


Fig. 2 Soil properties of the Jiangsu Marine clay

(4) Fit the plotted points by a straight line, of which corresponding slope is read as β_1. The intercept at the S_j axis gives β_0, while the point of intersection with the 45° line, gives the final consolidation settlement of the first stage.

(5) From the β_0 of the first stage construction to determine the undrained modulus E_u by inverse analysis (10).

(6) Determine the next stage construction settlement with the above known E_u (10), thus resulting in the shift distance of line.

(7) Assume the C_v remains constant during stage construction and settlement is small compared with the thickness of soft soils, this makes the line of next stage construction parallel to the first stage with the slope β_1.

(8) Predicting the final settlement of next stage construction from the intersection of the shifted line with the 45° line.

(9) Estimate the C_h and C_v from the value of β_1 with the equation (5) or (6).

2 Case study

2.1 Site and project description

Section A of Lianxu highway is a 31 km long high standard expressway connecting the port city Lianyugang to the national highway system of China. It was began to construction from Dec. 1999. There are 104 bridges or culverts or passways in this 31 km long section designed to connect embankments. The bottom width of the embankment is 40 m, while the height of embankment changes from 3 to 7 m.

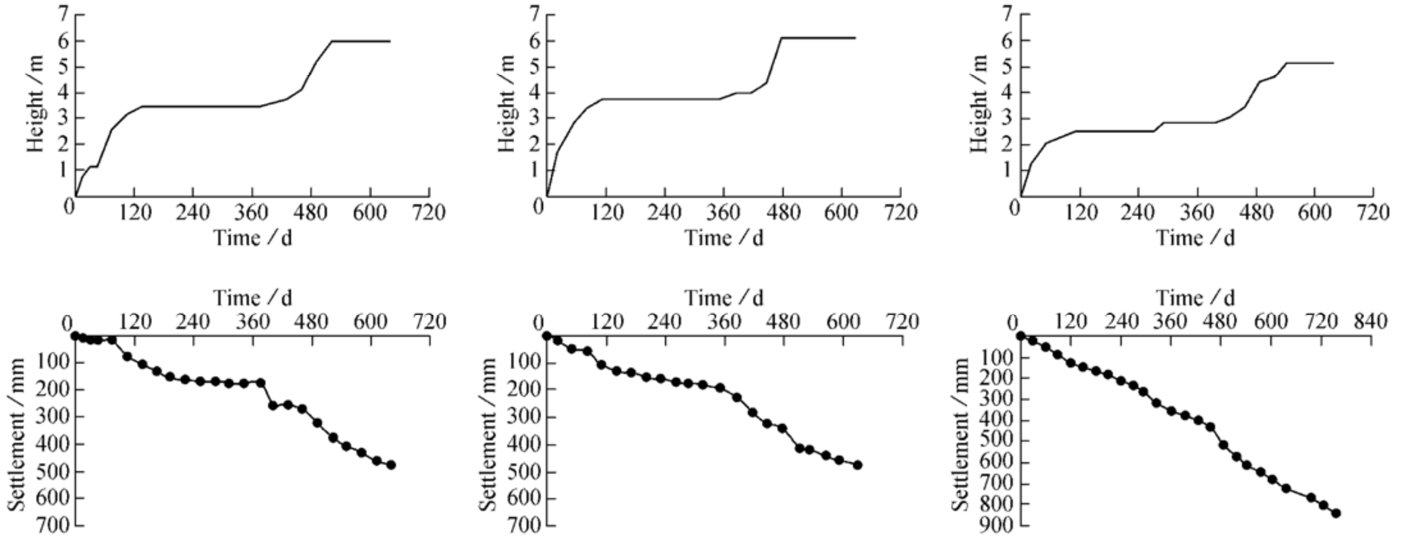
Based on the design code, the differential settlements between embankments and structures have to be controlled less than 10 cm. Post construction settlements of embankments have to be less than 30 cm during the post construction period of 15 years. It is clear that the magnitude and rates of the embankment settlements are the extremely important problem to make the project reliable and economical.

2.2 Subsurface conditions

The section A of Lianxu highway passes over the marine deposit plain. The typical subsoil profile consists of 0 to 3m think upper crust of stiff clay underlain by a 5.6 to 13m thick soft clay, which is named Jiangsu Marine clay. Blow this soft clay, lies alternating layers of stiff clay and dense sand extending to badrock with the varied thickness of 10 to 20m. The soil properties with depth are shown in Fig. 2.

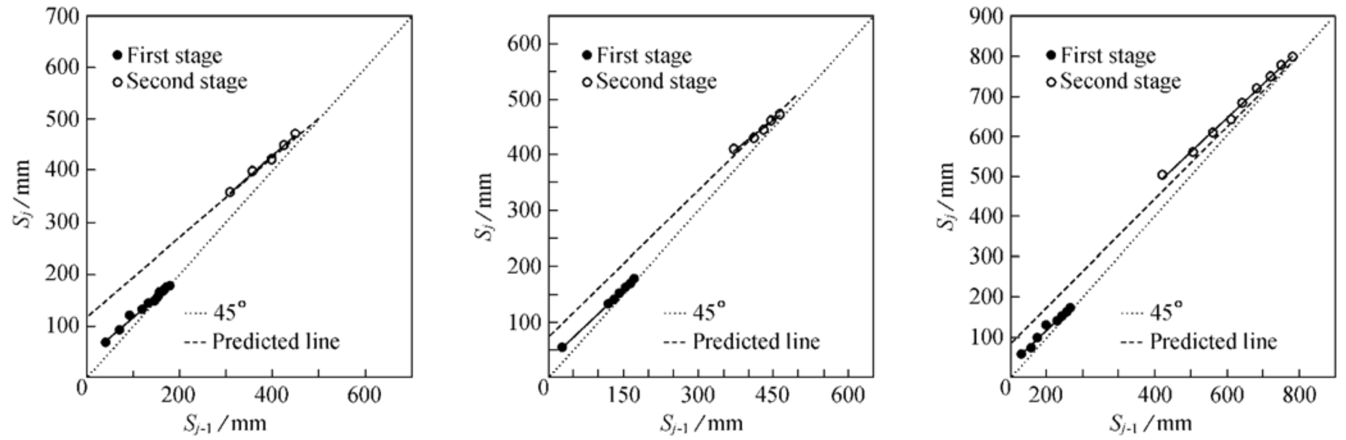
2.3 Soil improvement and embankment construction

Dry Jet Mixing and stage construction with sand blanket have been designed to reduce the total settlement and post construction settlement. The embankment filled with residual clay from Dec. 1999. After the first stage construction of 2.5~ 3.5 m high, about 6 months were left along for soil consolidation. The settlements are observed regularly by settlement plates. During the period of the first stage consolidation, some observational settlements are found to be larger than the corresponding designed total settlement. It is necessary to re-predict the behavior of the embankments based on the settlement observational results of the first stage construction, in order to modify the original design and make the reliable decision for next stage construction.



(a) K21+80 (b) K21+130 (c) K21+583

Fig. 3 Embankment heights and measured settlements with time



(a) K21+80 (b) K21+130 (c) K21+583

Fig. 4 Prediction of the final settlement of second stage from the first stage measurement

Table 1 Prediction results form the observational data

Location	First stage(Ⅰ)							
	Embankment height h_1 / m	Soft clay thickness H / m	$\beta_0(S_0^{\text{I}})$ / mm	β_1	E_u / kPa	E_u/c_u	C_v / ($m^2 \cdot a^{-1}$)	C_v(field)/ C_v(lab)
K21+ 80	3. 45	8. 2	65	0. 80	761	50	76	12
K21+ 130	3. 74	8. 0	38	0. 89	1377	92	38	6
K21+ 583	2. 50	9. 6	37	0. 90	1135	75	49	8

Location	Second stage(Ⅱ)				
	Embankment height h_2 / m	Increment of the height Δh / m	Immediate settlement S_0^{II} / mm	Predicted final settlement by presented method / mm	Predicted final settlement from measurement/ mm
K21+ 80	5. 95	2. 50	48	520	540
K21+ 130	6. 08	2. 34	26	590	550
K21+ 583	5. 16	2. 66	48	830	890

c_u is undrained shear strength, taken the approximate average value (15kPa) ; C_v is taken as 6. 1 m^2/ a, coressponding to the average value at 50 kPa.

2. 4 Prediction of the final settlement

The typical fill heights with time and measured ground surface settlements at the center of embankments with sand blankets are shown in Fig. 3. It can be seen that the settlement curve drops significantly between the first stage and second stage construction. The final settlements of the second stage construction are predicted from the first stage observational data by the stage observational method (Fig. 4, Table. 1) . It indicates that the predicted settlements are basically consistent with the measured settlement. Table 1 also shows the bake analyzed values of undrained elastic modulus E_u and coefficient of consolidation C_v based on the first stage observational data, giving ranges of E_u/c_u ratio of 50~ 100 and C_v(field)/C_v(lab) ratio of 6~ 12. It seems to be in the lower range of the E_u/c_u ratio for Jiangsu Marine clay compared with the ratio of 70~ 253 for Bangkok clay and other clays existing in the different literature[21]. The actual coefficient of consolidation appears one order of magnitude larger than the laboratory value, this resulting in the faster rate of measured settlement.

3 Conclusions

On the basis of theoretical derivation of Asaoka method and case study of Jiangsu Marine clay, this paper presented a Stage Observational Method for settlement prediction of embankments on soft ground with stage construction. The following conclusions can be given:

(1) Considering the available observational methods for ultimate settlement prediction, the Asaoka method may be successfully extended to make the settlement prediction for stage construction embankments.

(2) The immediate settlement S_e is verified to be equal to the intercept β_0 in the S_j and S_{j-1} space of the Asaoka method, therefore, the undrained modulus of soft ground can be obtained from the first stage construction measurements, this contributing to the more accurate estimation of immediate settlement of the next stage construction.

(3) Assuming the actual coefficient of consolidation and the thickness of the soft ground remain constant during stage construction, the shifting distances of the parallel lines with the slope of β_1 is equaled to the immediate settlements, which can be calculated with the inverse modulus from the first(last) stage construction.

(4) The distinct advantage of the recommended method is that the values of undrained modulus and coefficient of consolidation for next stage construction are inversely analyzed from the first (last) stage construction.

(5) From the case study, the value of E_u/c_u ratio ranges from 50 to 100 for Jiangsu Marine clay, while the actual coefficient of consolidation is almost one order of magnitude larger than the laboratory data.

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