Research Article

A Practical Design Method for Reducing Postconstruction Settlement of Highway Subgrade Induced by Soil Creep

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The postconstruction settlement of the bridge approach is usually uneven, which could create a bump in the roadway. Indeed, this is a typical situation at the bridge approach and requires a solution. One of the main causes of postconstruction settlement is the creep of soil. This paper is aimed at generalizing a new design method for controlling highway postconstruction settlement by replacing subgrade with expanded polystyrene (EPS). In the new method, the creep coefficient can be calculated based on the Yin-Graham EVP model. Thus, the relationship between the overloading ratio (OLR) and overconsolidation ratio (OCR) is obtained. The new method involves five steps: (a) determine the creep coefficient based on the relationship between the creep coefficient and overconsolidation ratio, (b) divide the ground into a suitable number of sublayers, (c) select groups of different overloading ratios and then calculate the average values of the additional stress and overconsolidation ratio for each sublayer under different OLRs, (d) calculate the postconstruction settlement under different OLRs, and (e) determine the replacement capacity for different sections. This method can be used for quantitative design according to different requirements of postconstruction settlement of foundation. Taking Huzhou Avenue as an example, the case study illustrates the calculation process of the new method in detail.

1. Introduction

The bridge approaches provide a smooth transition of cars from roadway pavements to bridge structures. However, the postconstruction settlement of bridge approaches is usually uneven, which could create a bump in the roadway. Indeed, this is a typical situation at the bridge approach and requires a solution.

The bump at bridge-head is a complicated technical problem. The creep of soil is one of the main causes of postconstruction settlement. The soil exhibits creep properties. Compared with primary consolidation settlement, creep settlement is small but significant, especially for soft clay. In the past several decades, extensive studies have been conducted on the creep of soft clay. Ladd et al. [1] first proposed the question of whether creep settlement occurs in the process of primary consolidation settlement. And there are two different views on whether the creep occurs during primary consolidation. They summed them up as Hypothesis A and Hypothesis B. Hypothesis A holds that creep occurs only in the secondary consolidation stage, and no creep occurs in the primary consolidation stage. Mesri et al. [2–4], Wang et al. [3], and Mesri and Vardhanabhuti [4] support Hypothesis A. However, Hypothesis B believes that the soil creep is caused by its own viscosity and occurs from the beginning of the primary consolidation process. It is supported by Bjerrum [5], Stolle et al. [6], Nash and Ryde [7], Yin et al. [8], Suklje [9], Bouchard et al. [10], Berre and Iversen [11], Leoni et al. [12], Karim et al. [13], and Nash and Brown [14]. As is known, with the effective stress changes, the creep always
exists actually, which means that Hypothesis B is reasonable. Based on Hypothesis B and the equivalent time concept, Yin and Graham [15–18] proposed a 1D elastic viscoplastic (EVP) model for creep behavior, which can be used to calculate the creep settlement. According to the EVP model, the creep coefficient is closely related to the over consolidation ratio (OCR).

Some compression tests [19–21] have shown that the creep coefficient decreases with the increase of OCR. Therefore, the use of a preload larger than the final construction load is an effective method to reduce postconstruction settlement [22–26]. However, in the actual project, for some sections, the preloading period is insufficient so that it is difficult to achieve the original effect within the time limit of the project. The method of replacing part of subgrade with lightweight materials to reduce the permanent load of subgrade can solve the problem [27, 28]. Expanded polystyrene (EPS) is one of the high-quality lightweight materials [29]. EPS has the characteristics of ultra-lightweight, compressibility resistance, self-reliance, water resistance, flame retardant, and so on. The density of the EPS material is generally 0.2 – 0.3 kN/m³, which is equivalent to 1/100–1/60 of the soil density. EPS has high compressive strength and varies with density, so it can be used as an embankment filling material in the elastic range of 80–140 kN/m². EPS is a synthetic resin foam containing independent bubbles that do not absorb water. The physical properties and mechanical indexes of the EPS material change little in the aging process, excellent aging resistance, and its aging life is more than 60 years.

It is important to determine the appropriate thickness of EPS to control the postconstruction settlement but there are only a few studies in this area. Chen et al. [30] suggest that consolidation, compression, and other parameters can be calculated according to the monitoring data, and the calculation program of foundation settlement reflecting the process of overloading-unloading and reloading should be compiled. Then, the relationship between different capacities of lightweight material and postconstruction settlement is obtained. Thus, the thickness of the lightweight material can be determined according to the allowable postconstruction settlement. Many factors are considered in this method, but it is difficult to be generalized and applied in engineering due to its complex calculation. Jiang et al. [31] come up with a formula to calculate the thickness. However, this formula also relies on monitoring data and the postconstruction settlement is only estimated according to the measured data. Therefore, this formula may not be used in the stage of design.

This paper is aimed at proposing a new practical design method for controlling highway postconstruction settlement by replacing subgrade with EPS. First, the functional relationship between the creep coefficient and overconsolidation ratio is established by fitting the one-dimensional compression test data. Second, the relationship between the overloading ratio (OLR) and overconsolidation ratio (OCR) is deduced. Then, groups of different OLR are selected and the postconstruction settlement under different OLRs is calculated. This method can be used for quantitative design according to different requirements of postconstruction settlement of foundation. And it can make the OLR greater than 1.3 without the limitation of foundation stability.

2. Creep Coefficient of Overconsolidated Soil

Buisman proposed the concept of secondary consolidation coefficient (C_a). As is shown in Figure 1, it is believed that the e - log t curve is close to a straight line after primary consolidation. The slope of the straight line part i is defined as secondary consolidation coefficient C_a.

\[
C_a = \frac{e_0 - e_1}{\log t_1 - \log t_0},
\]

where \(t_0\) is the time at the end of primary consolidation and \(t_1\) is any time after the end of primary consolidation.

However, Equation (1) is not applicable to the overconsolidated soil because overconsolidated soil has finished primary consolidation before test. In 1964, Crawford [32] conducted normally consolidated soil compressive rheological tests and plotted e – log p curves of different consolidation times. In 1967, Bjerrum made a creep diagram. As is shown in Figure 2, he divided the displacements which he observed in the actual engineering into "instant compression" and "delayed compression" and proposed that the delayed compression can be described with parallel lines in e – log p space.

Based on Bjerrum’s creep diagram, Yin-Graham proposed the 1-D EVP model, and the total strains can be written as follows:

\[
\varepsilon_z = \varepsilon_{zo} + \lambda \frac{C}{V} \ln \left( \frac{\sigma_z}{\sigma_{zo}} \right) + \psi \ln \left( \frac{t - t_o}{t_o} \right),
\]

where \(\varepsilon_{zo}\) is a reference strain and \(\varepsilon_z\) is the total strain. \(\sigma_{zo}'\) is a reference stress that corresponds, respectively, to the strain at the beginning of loading. For normally consolidated soil, \(\sigma_{zo}'\) corresponds to strain \(\varepsilon_{zo}\). V is the specific volume of the soil \((1 + e)\), that is, the volume occupied by unit volume of solids. So \(\lambda = C_e/2.303\) and \(\psi = C_{ac}/2.303\), where \(C_e\) and \(C_{ac}\) are the compression index and creep coefficient under logarithmic coordinates. Here, we call \(C_{ac}\) “creep coefficient” instead of the “secondary consolidation coefficient”, because Equation (2) considers creep occurs during and after “primary consolidation.” And \(t_o\) is a parameter that can be measured by one-dimensional compression test, which is usually taken as unit time or the boundary point between the primary consolidation and secondary consolidation [33]. \(t_e\) is called the equivalent time as defined by Yin and Graham.

According to Equation (2), the void ratio e, the effective stress \(\sigma\), and the equivalent \(t_e\) have a unique relationship.

\[
e = e_o - C_e \log \left( \frac{\sigma_z}{\sigma_{zo}} \right) - C_{ac} \log \left( \frac{t - t_o}{t_o} \right).
\]

As is shown in Figure 3, no matter if it is normal consolidation soil or overconsolidated soil, the zero point of time is taken as the loading start time of its corresponding normal
 consolidation condition. For example, point 2 in Figure 3 is under overconsolidation condition, and its corresponding normal consolidation condition is point 5 on the normal consolidation line. The time corresponding to point 5 is the beginning time. And $t_e$ is the equivalent time that is from point 5 to point 2. Such a time coordinate system combines normal consolidation and overconsolidation into a unified time coordinate system, so it is called an absolute time coordinate system. Now, $t_e$ can be found from

$$C_{nc0} \lg \left( \frac{t_e + t_o}{t_o} \right) = (C_c - C_e) \lg \left( \frac{\sigma'_{ec}}{\sigma_{ec0}} \right),$$

where $C_{nc0}$ is the normal consolidation soil creep coefficient and $C_e$ is the expansion coefficient. From which

$$t_e = t_o \left( \frac{\sigma'_{ec}}{\sigma_{ec0}} \right)^{(C_c - C_e)/C_{nc0}} - t_o.$$ (5)

Let

$$\text{OCR} = \frac{\sigma'_{ec}}{\sigma_{ec0}} = \frac{C_c - C_e}{C_{nc0}}.$$ (6)

$t_e$ can be expressed as follows:

$$t_e = t_o \left( \text{OCR} \right)^{\delta} - t_o.$$ (7)

According to Equation (7), $t_e$ is a parameter related to OCR, and it can reflect the stress history and the state of soil. For overconsolidated soil, the creep coefficient of overconsolidated soils can be expressed as

$$C_{oc} = \frac{\Sigma - e_2}{\Sigma - e_1} \lg \left( \frac{(t_{e2} + t_o)/(t_{e1} + t_o)}{\Sigma - e_1} \right)$$

$$= \frac{\Sigma - e_2}{\Sigma - e_1} \lg \left( (t_{e1} + \Delta t + t_o)/(t_{e1} + t_o) \right)$$

$$= \frac{\Sigma - e_2}{\Sigma - e_1} \lg \left( 1 + (\Delta t/(t_{e1} + t_o)) \right),$$ (8)

where $t_{e1}$ and $t_{e2}$ are the equivalent time; $e_1$ and $e_2$ are the void ratios at equivalent time $t_{e1}$ and $t_{e2}$, respectively; and $\Delta t$ is the current load duration from $t_{e1}$ to $t_{e2}$.

According to Equations (7) and (8), the creep coefficient is not a constant. It can be expressed as a function with over-consolidation ratio.

$$C_{oc} = f(OCR).$$ (9)

### 3. The Relationship between Overconsolidation Ratio (OCR) and Overloading Ratio (OLR)

The maximum value of load in the past, namely, the preload, divided by the present value of load, is defined as the overloading ratio (OLR). Overload ratio (OLR) was proposed to reflect overload state, which can be expressed as follows:

$$\text{OLR} = \frac{p_o}{p_f}.$$ (10)

where $p_o$ is the preload, that is, the load under the condition of overload preloading, $p_f$ is the present value of load, that is, the final construction load on the ground surface.

The maximum value of effective stress in the past, namely, the preconsolidation pressure, divided by the present value of effective stress of effective stress, is defined as the overconsolidation ratio (OCR).

$$\text{OCR} = \frac{\sigma_{ec}}{\sigma_{o}}.$$ (11)

where $\sigma_{o}$ is the present effective stress and $\sigma_{ec}$ is the preconsolidation pressure.

When the load on the ground surface changes, the stress state of each point in the soil stratum will change, and OCR will also change. For example, as is shown in Figure 4, point A is under normal consolidation condition before loading. That is, $\sigma_{o}$ is equal to $\gamma z$.

In soil mechanics, when load $p_o$ is applied to the ground surface, the vertical additional stress $\sigma_m$ is equal to $\alpha p_o$. Here, $\alpha$ is the additional stress coefficient which can be calculated based on the depth of soil and the load distribution type. It is convenient that we can look up the additional stress coefficient table to determine its value. And when final load $p_f$ is applied to the ground surface, the vertical additional stress $\sigma_f$ is equal to $\alpha p_f$. So, the OCR of point A can be expressed as follows:

$$\text{OCR} = \frac{\sigma_{o} + \sigma_m}{\sigma_{o} + \sigma_f} = \frac{\gamma z + \alpha p_o}{\gamma z + \alpha p_f}.$$ (12)

As is shown in Figure 4,

$$H = h + \Delta h + h_o,$$ (13)

$$p_f = \gamma h + \gamma E \Delta h + \gamma H,$$ (14)

$$p_o = \gamma H = \gamma (h + \Delta h + h_o).$$ (15)
where \( \gamma, \gamma_E, \gamma_i, \) and \( \gamma_s \) indicate the unit weight of filling soil, EPS, soft soil, and pavement, respectively; \( h, \Delta h, \) and \( h_s \) indicate the thickness of soft soil, EPS, and pavement, respectively; and \( H \) is the designed height of embankment fill.

Let us establish the relationship between the OCR and OLR. Based on Equations (10) and (11),

\[
OCR = \frac{\gamma_i z + \alpha(\gamma h + \gamma_E \Delta h + \gamma_i h_s)}{\gamma_i z + \alpha(\gamma h + \gamma_E \Delta h + \gamma_i h_s)}
\]
\[
= \frac{\gamma_i z + \alpha(\gamma h + (\gamma - \gamma_E)\Delta h + (\gamma_i + (\gamma - \gamma_i))h_s)}{\gamma_i z + \alpha(\gamma h + (\gamma - \gamma_E)\Delta h + \gamma_i h_s)}
\]
\[
= 1 + \left( \frac{(\gamma - \gamma_E)\Delta h + (\gamma - \gamma_i)h_s}{\gamma h + \gamma_E \Delta h + \gamma_i h_s + (\gamma_i z / \alpha)} \right).
\]

\[
(16)
\]

\[
OLR = \frac{\gamma(h + \Delta h + h_s)}{\gamma h + \gamma_E \Delta h + \gamma_i h_s}
\]
\[
= \frac{\gamma h + (\gamma_E + (\gamma - \gamma_E))\Delta h + (\gamma_i + (\gamma - \gamma_i))h_s}{\gamma h + \gamma_E \Delta h + \gamma_i h_s}
\]
\[
= 1 + \left( \frac{(\gamma - \gamma_E)\Delta h + (\gamma - \gamma_i)h_s}{\gamma h + \gamma_E \Delta h + \gamma_i h_s} \right).
\]

\[
(17)
\]

According to Equations (14) and (15),

\[
1 - \frac{1}{OCR - 1} = \frac{\gamma_i z}{\alpha(\gamma - \gamma_E)\Delta h + (\gamma - \gamma_i)h_s}.
\]

\[
(18)
\]

Let

\[
\beta(z) = \frac{\gamma_i z}{\alpha(\gamma - \gamma_E)\Delta h + (\gamma - \gamma_i)h_s}.
\]

\[
(19)
\]

Thus, OCR, OLR, and \( z \) have a relationship:

\[
OCR = 1 - \frac{1}{1/(OLR - 1) + \beta(z)}.
\]

\[
(20)
\]

4. The New Method for Controlling Postconstruction Settlement

4.1. Procedures of Applying the Practical Design Method. The new method for controlling postconstruction settlement involves the following 5 steps:

(a) Determine the creep coefficient. Based on the Yin-Graham EVP model, the functional relationship between the creep coefficient and overconsolidation ratio is established by fitting the one-dimensional compression test data
(b) Divided the ground into a suitable number of sub-layers. Each sublayer within a same soil layer should not be overly thick. The thickness of each sublayer should be controlled within 2 m-4 m. For each sublayer, it is assumed that pressure is uniformly distributed.

(c) Select groups of different OLRs and calculate the average values of the additional stress and OCR for each sublayer under different OLRs. The OLR usually ranges from 1.1 to 1.6 in actual projects. Based on Equation (19), the additional stress and OCR at the center point of each sublayer are calculated and the values are taken as the average additional stress and OCR for each sublayer.

(d) Calculate the postconstruction settlement under different OLRs. Based on the functional relationship between \( C_{ae} \) and OCR, the creep coefficient of each layer is determined according to the average over-consolidation ratio for each sublayer. According to Equation (20), the settlement of each sublayer was calculated and the total postconstruction settlement of ground can be calculated as follows:

\[
s = \sum_{i=1}^{n} \frac{H_i}{1 + e_{oi}} C_{aei} \log \left( \frac{t_1 + \Delta t}{t_1} \right),
\]

where \( s \) is the total postconstruction settlement of ground, \( H_i \) is the thickness of each sublayer, \( C_{aei} \) is the creep coefficient of each sublayer, \( t_1 \) is the preloading period, and \( \Delta t \) is the service period which is usually taken as 15 years.

(e) Correct the settlement value with the safety factor \( \mu \) and determine the overload ratio and the replacement capacity under the requirements of postconstruction settlement.

4.2. Advantages of the New Method. On the one hand, the subgrade soils become overconsolidated soil after replacement with EPS, so the creep coefficient is greatly reduced. As a lightweight material, EPS itself has the characteristics of ultralightweight, compressibility resistance, self-reliance, water resistance, flame retardant, and so on. Therefore, this method can better control the postconstruction settlement.

On the other hand, this method can be used for the quantitative design according to different requirements of postconstruction settlement of foundation. In the process of the engineering design, the calculation of postconstruction settlement is often calculated by empirical formula or correction coefficient. This is often unable to meet the strict requirements of some engineering. Using the creep coefficient, this method can realize the quantitative calculation of postconstruction settlement.

Besides, this method can make the overloading ratio greater than 1.3 without the limitation of foundation stability. It is necessary to control the overloading ratio to ensure the stability of the foundation when using the overload preloading method for ground treatment. Thus, when the overloading is relatively small, a longer preloading time is needed to ensure the effect of controlling the postconstruction settlement, which would prolong the construction period. This method can make the overloading ratio greater than 1.3, which is like a strategy using space to exchange for time.

5. Case Study

5.1. Project Background. The considered Huzhou Avenue is constructed on soft clay on the Huzhou plain, southeast of the city of Huzhou in China. As is shown in Figure 5, the bridge approach is about 140 m long, which is divided into 5 transition sections (S1 to S5) and 1 general section (GS). The soft clay beneath it is about 13 m deep. In order to provide a smooth transition of vehicles from highway pavements to bridge structures, the design scheme is different for each section. Cement-soil mixed piles are used in S1 and S2. EPS lightweight materials are used in S3, S4, and S5. The plastic drainage plate is used in all sections.

The soft clay has high water content, a high void ratio, high compressibility, low strength, and low permeability. The soil profile is depicted in Figure 6, obtained from geological survey. The soil consists of 2 layers: (a) hard crust and (b) soft clay.
5.2. One-Dimensional Compression Test

5.2.1. Test Apparatus. As is shown in Figure 7, the sixteen automatic pneumatic consolidation apparatus is adopted to carry out one-dimensional compression test. The ring knife is 2 cm high, and the base area is 45.6 cm\(^2\). Compared with traditional apparatus, the system has the advantage of automatic data acquisition during the test and overcomes the disadvantages of traditional manual recording. In order to ensure the reliability of the test results, the apparatus was proofread before the test.

5.2.2. Test Scheme and Description. In order to determine the stress history of the ground soils, the preconsolidation pressure should be first determined. Casagrande proposed an empirical graphical method using the \( e - \lg p \) curve to obtain the maximum effective stress that had acted on the clay in the past. It is known through tests that the soft clay belongs to normally consolidated soil. The sample soils are taken from a depth of 5 m, and the preconsolidation pressure is about 110 kPa. In order to ensure that the maximum load is greater than the preconsolidation pressure, it is set as 150 kPa. The test loading path is divided into overloading, unloading, and reloading in order to simulate the actual construction condition. The soft clay is overconsolidated after reloading. For excluding the influence of the loading ratio factor, the loading ratio of each group is set as 1. Since the overconsolidation ratio is small and the creep coefficient changes greatly, the overconsolidation ratios are set as 1.1, 1.2, 1.4, and 1.8. It takes a long time for the creep coefficient to stabilize, so the duration of the last stage test should be at least 7 d. The specific scheme for one-dimensional compression tests is shown in Table 1.

5.2.3. Test Results. Figure 8 shows the \( s - \lg t \) curve of sample 1. Since the sample soil belongs to normally consolidated soil, it is obvious that the boundary between the primary and secondary consolidations is at about \( t_0 = 100 \) min. According to Equation (1),

\[
C_a = \frac{e_0 - e_1}{\lg t_1 - \lg t_0} = \frac{1.469 - 1.437}{\lg 1440 - \lg 100} = 0.0271. \tag{22}
\]

Figure 9 shows the \( e - \lg t \) curve of soil sample 2, sample 3, sample 4, and sample 5 under the last stage load. From Figure 9, we can learn that the lines of all samples are smooth after 100 min, so \( t_0 \) is 100 min. And the duration should be reduced by 100 minutes, so \( \Delta t = 7d - 100 \) min = 9980 min. Since each stage of load, except the last stage, lasts for 1 day, the equivalent time should be taken as 1 day. According to Equation (8), the creep coefficient can be calculated.

Taking sample 2 as an example, \( t_c = 1d = 1440 \) min, \( t_o = 100 \) min, \( \Delta t = 9980 \) min, \( e_1 = 1.245 \), and \( e_2 = 1.228 \). So, when OCR is 1.1, the creep coefficient.

\[
C_{ae} = \frac{e_1 - e_2}{\lg (1 + (\Delta t/(t_c + t_o)))} = \frac{1.245 - 1.228}{\lg (1 + (9980/(1440 + 100)))} \approx 0.0197. \tag{23}
\]

The creep coefficients under each overconsolidation ratio are calculated as shown in Table 2.

5.3. Calculate the Postconstruction Settlement. As is shown in Figure 11, to facilitate the analysis, it is assumed that \( p_o \) is divided into 2 stages that are abruptly applied on the ground
surface. When the final stage is applied up to $t_2$, the additional surcharge is replaced with lightweight EPS, and the preload is reduced from $p_{0}$ to $p_{m}$. And then, the pavement is laid and the load is up to $p_f$.

As is shown in Figure 6, the thickness of hard crust is approximate 1 m. Due to its low compressibility, the post-construction settlement of this layer is negligible. The designed height of embankment fill $H$ is 4.4 m. The unit weight of filling soil $\gamma$ is taken as 20 kN/m$^3$. According to Equation (13),

$$p_{0} = \gamma H = 20 \times 4.4 = 88 \text{ kPa}. \quad (25)$$

The designed thickness of pavement structure layer $h_s$ is 0.9 m. And its unit weight $\gamma_s$ is taken as 23 kN/m$^3$. When the thickness of EPS $\Delta h$ is taken as 0.5 m, according to Equations (13) and (15), the final load $p_f$ and OLR are calculated below.

$$p_f = \gamma h + \gamma_E \Delta h + \gamma_s h_s = 20 \times 3 + 0.2 \times 0.5 + 23 \times 0.9 \quad (26)$$

$$= 80.47 \text{ kPa},$$

$$\text{OLR} = \frac{p_{0}}{p_f} = \frac{88}{80.47} = 1.093. \quad (27)$$

For the first soil layer, the depth of the middle point $z = 1$ m. Having looking up the additional stress coefficient table, we obtain $\alpha = 1.0$. According to Equations (18), (19), and (21),

$$\beta(z) = \frac{\gamma' z}{\alpha (\gamma - \gamma_E) \Delta h + (\gamma - \gamma_E) h_s} = \frac{16 \times 1}{1 \times (20 - 0.3) \times 0.5 + (20 - 23) \times 0.9} = 1.838, \quad (28)$$

Table 1: Scheme for one-dimensional compression tests.

<table>
<thead>
<tr>
<th>Sample</th>
<th>OCR</th>
<th>Load path and duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.0</td>
<td>$37.5 \text{ kPa (1 d)} \rightarrow 75 \text{ kPa (1 d)} \rightarrow 150 \text{ kPa (1 d)} \rightarrow 136.4 \text{ kPa (7 d)}$</td>
</tr>
<tr>
<td>2</td>
<td>1.1</td>
<td>$37.5 \text{ kPa (1 d)} \rightarrow 75 \text{ kPa (1 d)} \rightarrow 150 \text{ kPa (1 d)} \rightarrow 125 \text{ kPa (7 d)}$</td>
</tr>
<tr>
<td>3</td>
<td>1.2</td>
<td>$37.5 \text{ kPa (1 d)} \rightarrow 75 \text{ kPa (1 d)} \rightarrow 150 \text{ kPa (1 d)} \rightarrow 112.2 \text{ kPa (7 d)}$</td>
</tr>
<tr>
<td>4</td>
<td>1.4</td>
<td>$37.5 \text{ kPa (1 d)} \rightarrow 75 \text{ kPa (1 d)} \rightarrow 150 \text{ kPa (1 d)} \rightarrow 107.3 \text{ kPa (7 d)}$</td>
</tr>
<tr>
<td>5</td>
<td>1.8</td>
<td>$37.5 \text{ kPa (1 d)} \rightarrow 75 \text{ kPa (1 d)} \rightarrow 150 \text{ kPa (1 d)} \rightarrow 83.3 \text{ kPa (7 d)}$</td>
</tr>
</tbody>
</table>

Note: the arrow direction in the loading path represents the next level stress. The number before the brackets is the value of the load, and the number in the brackets is the duration of the load. For example, 37.5 kPa (1 d) represents that the load is 37.5 kPa (duration is 1 day).

Figure 7: Automatic consolidation apparatus.

Figure 8: $s - \lg t$ curve.
In this project, the timing of replacement is the timing of unloading. As the timing of unloading is mainly determined based on the degree of primary consolidation, the timing of replacement could be determined with traditional method. The preloading period lasts 1 year, so $t_1 = 1$ year. The postconstruction settlement at the end of the service period can be calculated according to Equation (19).

$$s_1 = H_1 \frac{C_{ae} \varepsilon_0 \log \left( \frac{t_1 + \Delta t}{t_1} \right)}{1 + \frac{\varepsilon_0}{C_{ae}}} = \frac{2}{1 + \frac{1.574}{1}} \times 0.0227 \log \left( \frac{1 + 15}{1} \right) = 0.021 \text{m}.$$  

The postconstruction settlement of other soil layers is calculated in turn, and the calculation results are shown in Table 3.

Actually, the degree of consolidation cannot reach 100%, so the calculated postconstruction settlement should be corrected. The correction factor $\mu$ can be evaluated according to the degree of consolidation. The correction factor $\mu$ is an empirical coefficient. Here, according to existing engineering experience, as is shown in Table 4, we suggest the value of the correction factor should be determined based on the degree of consolidation after preloading. In this project, the degree of consolidation after preloading is about 80%, so the correction coefficient is 1.3.

According to the above calculation process, the postconstruction settlement under different OLRs is calculated as Table 5.

The allowable postconstruction settlement of the general section is 30 cm, which is the requirement in the specification. The longitudinal grade allowable value is 4‰. As is shown in Figure 5, the distance between the general section and Section 3 is 65 m. If the OLR of Section 3 is set as 1.09, the longitudinal grade is $(300 - 141.7)/65000 = 2.4\% < 4\%$.

As is shown in Figure 12, the settlement curve of the cross-section is distributed in parabolic shape roughly. However, the calculated overloading ratio above is that of the
Table 3: Settlement calculation results.

<table>
<thead>
<tr>
<th>i</th>
<th>$H_i$</th>
<th>$a$</th>
<th>$\beta$</th>
<th>OCR</th>
<th>$C_{uv}$</th>
<th>$s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2(1.0)</td>
<td>1</td>
<td>4.900</td>
<td>1.062</td>
<td>0.0227</td>
<td>0.021</td>
</tr>
<tr>
<td>2</td>
<td>3(4.5)</td>
<td>1</td>
<td>7.351</td>
<td>1.054</td>
<td>0.0231</td>
<td>0.032</td>
</tr>
<tr>
<td>3</td>
<td>2(7.0)</td>
<td>0.95</td>
<td>18.054</td>
<td>1.034</td>
<td>0.0242</td>
<td>0.023</td>
</tr>
<tr>
<td>4</td>
<td>2(9.0)</td>
<td>0.93</td>
<td>23.712</td>
<td>1.028</td>
<td>0.0245</td>
<td>0.023</td>
</tr>
<tr>
<td>5</td>
<td>2(11.0)</td>
<td>0.89</td>
<td>30.284</td>
<td>1.024</td>
<td>0.0248</td>
<td>0.023</td>
</tr>
<tr>
<td>6</td>
<td>2(13.0)</td>
<td>0.86</td>
<td>37.038</td>
<td>1.020</td>
<td>0.0251</td>
<td>0.023</td>
</tr>
</tbody>
</table>

Note: the number in parenthesis is the depth of the middle of each layer.

Table 4: Correction factor.

<table>
<thead>
<tr>
<th>The degree of consolidation</th>
<th>$\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;95%</td>
<td>1.1</td>
</tr>
<tr>
<td>85%–95%</td>
<td>1.2</td>
</tr>
<tr>
<td>75%–85%</td>
<td>1.3</td>
</tr>
<tr>
<td>&lt;75%</td>
<td>1.4</td>
</tr>
</tbody>
</table>

$s = \mu \times \bar{s} = 1.3 \times 145 = 188.5$ mm.

Table 5: Postconstruction settlement under different OLRs.

| $\Delta h$ | OLR | $s$ (mm) | $|s|$ (mm) |
|------------|-----|----------|----------|
| 0.5        | 1.09 | 145      | 188.5    |
| 1.0        | 1.26 | 126      | 163.8    |
| 1.5        | 1.45 | 109      | 141.7    |

Figure 12: Settlement curve of cross-section of embankment.

midpoint of each section. So, the cross-section can be optimized to get more economical. The specific optimization content will be introduced in another article.

6. Conclusions

Based on practical engineering, a new design method for controlling postconstruction settlement is proposed in this paper. Main conclusions are drawn as follows:

(a) Based on the 1D EVP model and the concept of equivalent time, the functional relationship between the creep coefficient and overconsolidation ratio can be established by fitting one-dimensional compression test data. It is found that the creep coefficient decreases with the overconsolidation ratio increasing.

(b) The relationship between the overloading ratio and overconsolidation ratio is deduced. In practical engineering, the overconsolidation ratio can be changed by adjusting the overloading ratio, and then, the creep coefficient can be changed to control the post-construction settlement.

(c) The new method can be used for the quantitative design according to different requirements of postconstruction settlement of foundation. The case study shows that the method is operable in engineering.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

References


