Research Article

A Novel Incipient Evaluation Method for Postconstruction Settlement by Using a Statistic Approach with Time-Extended Loading Test

Baoning Hong,1,2,3 Hao Shan,1,2,3 Xin Liu,1,2,4 Fenqiang Xu,5 and Ke Sheng1,2,3

1Key Laboratory of Ministry of Education for Geomechanics and Embankment Engineering, Hohai University, Nanjing 210098, China
2Jiangsu Research Center for Geotechnical Engineering Technology, Hohai University, Nanjing 210098, China
3Geotechnical Research Institute, Hohai University, Nanjing 210098, China
4Research Institute of Tunnel and Underground Engineering, Hohai University, Nanjing 210098, China
5Architectural Engineering Institute, Nanjing Institute of Technology, Nanjing 211167, China

Correspondence should be addressed to Xin Liu; liuxin100@hhu.edu.cn

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This paper proposes an incipient assessment method for postconstruction settlement of highway subgrade by using statistical analysis approach with an improved static loading test method, time-extended loading test. The time-extended loading residual settlement $S_r(t)$ and settlement rate $V_s(t)$ are calculated from the field test data. The test procedure and the corresponding experimental validations are presented. Based on the field test data, a probabilistic model is built to bridge the final residual settlement and the actual postconstruction settlements. The proposed time-extended loading test based assessment system has been validated through three operating and well-documented road sections. According to the validation results, the construction quality can be accurately evaluated at an early stage and the corresponding remedial measures can be applied timely.

1. Introduction

Traditional incipient quality inspection methods for piled-soil composite subgrades of highways are not accurate enough. The conventional assessment system sometimes cannot reveal the true construction quality. Large postconstruction settlement can be detected and bridge bumps can be observed in lots of the road construction projects whose composite subgrades satisfied the traditional incipient quality inspection requirements [1–3]. Hence, it is necessary to develop accurate incipient assessment method for evaluating the postconstruction settlement with the consideration of the behavior of settlement process. An accurate assessment index ensures the safety and comfort of the vehicles and the passengers during the operation period of the road [4–8]. Many scholars and technicians used theoretical analysis methods [9–11], numerical simulation approaches [12–15], or field measurement data fitting methods [16–18] to study the postconstruction settlement of highways. According to the soil modulus amplification factor for creating the soil deformation, Zhou Tonghe et al. [19] proposed a theoretical method for calculating postconstruction settlement of composite subgrades. Ding Mingji [20] analyzed the relationships between the design parameters of the Cement Fly-Ash Gravel (CFG) piles and plates and the postconstruction settlement of a high-speed railway by using numerical simulation method. Kermani et al. [21] proposed two methods for estimating postconstruction settlement: (1) using subgrade height to estimate postconstruction settlement; (2) using stress-strain behavior of compacted layer during construction to predict the stress-strain-time change of subgrades. Chen Yuanhong et al. [10] proposed a power polynomial prediction method for postconstruction settlement of soft foundation embankment based on field monitoring data. Advanced heuristic algorithm based estimation methods [22, 23] have also been proposed for tackle problem of the multi-input impact to the settlement estimation. However, seldom of the study in the literature focuses on the investigation of the early assessment
method for the postconstruction settlement of composite subgrades by using constructive quality inspection methods. At the same time, certain deficiencies exist in the traditional evaluation methods. For example, the correctness of the system parameters affects the accuracy of the theoretical analysis and numerical simulation results. The time cost of the long-term field monitoring method is expensive and it is hard to control the precision of the monitor location.

To ease the deficiencies of the traditional methods, a time-extended loading test method acted as an improvement of the static load test has been proposed in this paper. Based on the field measurement from the time-extended loading test, the incipient assessment indexes have been developed through statistical analysis approaches. The prediction method of the postconstruction settlement has been provided as well. Instead of replacing the existing evaluation method, the proposed method aims at improving the existing method as well as enriching the existing quality inspection index system. In addition to strength inspection, the proposed evaluation method can perform strength-settlement detection. Besides, early remedial actions can be implemented based on the proposed assessment indexes to reduce postconstruction settlement in the early stage.

The main contributions of this paper can be concluded as follows: (1) a novel time-extended loading test is proposed in this paper for minimizing the construction condition impact and enhance the accuracy of the prediction results; (2) a probabilistic model for predicting the postconstruction settlement by using time extend loading test results is developed by using 38 field data with diverse construction conditions; (3) the proposed method and indexes have been validated through three operated road sections.

2. Time-Extended Loading Test Method

The time-extended loading (TEL) test is a supplementary test for accurately evaluating the postconstruction settlement of pile-soil composite subgrade. Apart from the approach that using the elastic cushion in the experiment mimics the functions of the cushion in practice, the additional static weight has been loaded on the cushion and the settlement changes will be recorded.

2.1. Necessity of Time-Extended Loading Test. Cushion plays a critical role in the bearing system of the pile-soil composite subgrade. Because of the mass of the subgrade, the vehicles, and the dynamic adjustment from the cushion, the stress stabilization process of the pile-soil composite subgrade generally takes a long time. Hence, the stress state of the pile-soil composite subgrade cannot reach a stable state under the conventional static loading test. Because of this deficiency of the conventional static loading test, the estimation of the postconstruction settlement may not be accurate enough. With the support from the Guangdong Province Transportation Engineering Quality Supervision Station and the Foshan Highway Bridge Engineering Monitoring Station, the authors have collected the postconstruction settlement data from 157 different high-standard roads in Guangdong area. All the monitored high-standard roads satisfied with

the requirements in the static loading test and operate for 2–5 years. The pile types of sample roads include pipe piles, cement mixing piles, CFG piles, and powder jet piles. Meanwhile, the traffic flows, geological composition, and fill height of each road section are also different. Hence, the settlement data of the selected road samples have certain representativeness. The hyperbolic curve method has been used to fit the field postconstruction settlement data of each section for predicting their postconstruction settlement after 15-year operation. The corresponding prediction results are concluded in Figure 1. The predicted 15-year postconstruction settlement data are considered as the actual settlement data in this paper and denote as $S_f$.

According to Figure 1, the maximum and minimum postconstruction settlements are 321.15 mm and 8.78 mm, respectively. 54.78% of the total road sections have more than 100 mm postconstruction settlement. 30% of the road sections fail to satisfy the regulations. In conclusion, the traditional evaluation method, static loading test method, cannot provide an accurate prediction on the final postconstruction settlement since the stress state of the pile-soil composite subgrade is not stabilized during the static loading test and the model of the cushion is unrealistic. Therefore, it is possible to improve the detection and evaluation accuracies of the composite subgrade postconstruction settlement by extending the loading test time and obtaining settlement information under near steady-state condition. To approach the near steady-state condition of the composite subgrade, the TEL test based assessment method is proposed and discussed in the following sections.

2.2. Time-Extended Loading Test Design and Procedure. As mentioned in the previous section, the stress ratio of the pile-soil can be used to identify whether a pile-soil composite subgrade is in a stable stress state. The stress ratio of the pile-soil tends to be stable when the subgrade is loaded. In the literature, many scholars and engineers have carried out some studies [24–27] related to the behavior of the pile-soil stress ratio and they have obtained useful conclusions.
### Table 1: Parameters of elastic rubber cushions.

<table>
<thead>
<tr>
<th>Composite Subgrade Type</th>
<th>Elastic cushion parameters</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexible pile</td>
<td>( h/E = 3 ) to ( 10 ) [mm/MPa] ((h \geq 20 \text{ mm}))</td>
<td>For ( h = 20 \text{ mm} ), the range of ( E ) is ( 2 ) to ( 8 ) MPa;</td>
</tr>
<tr>
<td>Semi-rigid pile</td>
<td>( h/E = 6 ) to ( 15 ) [mm/MPa] ((h \geq 40 \text{ mm}))</td>
<td>For ( h = 40 \text{ mm} ), the range of ( E ) is ( 4 ) to ( 8 ) MPa;</td>
</tr>
<tr>
<td>Rigid pile</td>
<td>( h/E = 9 ) to ( 20 ) [mm/MPa] ((h \geq 60 \text{ mm}))</td>
<td>For ( h = 60 \text{ mm} ), the range of ( E ) is ( 6 ) to ( 8 ) MPa;</td>
</tr>
</tbody>
</table>

Based on the observation from the field test results and corresponding theoretical analysis, the adjustment rate of the cushion can be increased when a composite subgrade is statically loaded by two times of its designed bearing capacity. Under this situation, a nearly stabilized pile-soil stress ratio under rated load can be achieved within a short time. The similar phenomenon has been observed in 90% of the author’s field tests: the pile-soil final stress ratio in rated load condition of a composite subgrade can reach within 48 hours by statically loading the composite subgrade with two times of its designed bearing capacity. Therefore, the loading value in the TEL test is selected as two times the rated load and the extended test time is 48 hours.

After determining the weight and time of the TEL test, the detailed test procedures can be concluded as four parts: preparation, loading, data acquisition, and observation of the settlement-time relations.

1. Loading value determination and classification: first, the design value of the composite subgrade bearing capacity was determined. The experiment loading value was two times of the design value and it equals the maximum loading value of the single pile composite subgrade in the conventional static load test. According to the requirements in the specific regulations, the loading process can be divided into 8-12 levels, and the loading time interval of each level was controlled.

2. Test cushion selection: to emulate the adjustment effect of a cushion accurately, 8-10 cm sand cushions combined with an elastic rubber cushion were used. The elastic rubber cushion thickness \( h \) and the elastic modulus \( E \) are provided in Table 1. Usually, the cement mixing piles, Dry Jet Mixing Piles, and high-pressure jet grouting piles are classified as flexible piles \([28, 29]\). CFG piles are classified as semirigid piles \([30, 31]\). Pipe piles and bored piles are classified as rigid piles \([32, 33]\).

3. Installation of loading devices: the test used a pressure platform with counterforce setting. The pressure platform acted as a load counterforce, and the load greater than the maximum testing load was added to the platform before the beginning of the TEL test. The hydraulic jack was used for control the test loading level. A circular plate with a diameter of 1.26 m and an area of 1.25 m\(^2\) was adopted as the load plate; see Figure 2.

4. Data acquisition system layout: four dial-gauges were installed at the four corners of the platen. The settlement acquisition frequency was determined based on the test requirements. The accuracy of the dial-gauges is 0.01 mm.

5. Observations of settlement and time relationships: during the loading phase, the data was recorded according to the requirements of the standards. The first six reading time intervals of the settlement in the TEL test are 10 minutes, 10 minutes, 15 minutes, 15 minutes, 15 minutes, and 15 minutes. Then the settlement was measured every 30 minutes.
(6) Data analysis: from the collected test data, the corresponding settlement values at each time point during the TEL test were extracted. The detailed calculation and analysis processes are shown in Section 3.

2.3. Field Test of Time-Extended Loading Test. The proposed TEL method has potential to minimize the construction impact to the estimation of the postconstruction settlement. For validating this property of the proposed TEL method, the single pile composite subgrade field tests with 38 diverse pile types and under different test conditions were performed. The 38 test sites are selected based on the static loading test results of hundreds of projects in Guangdong Province. The pile types can be concluded as mixing cement piles representing flexible piles, CFG piles representing semirigid piles, and prefabricated pipe piles representing rigid piles. Tests nos. 1-12 are flexible piles, tests nos. 13-26 are semirigid piles, and test nos. 27-38 are rigid piles. All the settlement-time data during the TEL test is recorded for further analysis purposes.

As mentioned in the Section 2.1, the pile-soil stress ratio after applying the proposed TEL test is close to the pile-soil stress ratio under steady-state condition. To validate this argument, an example field test comparison is shown in Figure 3.

According to Figure 3(a), the stress ratio of a road section after the second year operation was 8.9 and it tended to stable around 9. According to Figure 3(b), the stress ratio after TEL test in the same road section was 9.21 which was close to the field measurement data. Hence, the proposed TEL test can effectively shrink the settlement process and minimize the impact of the construction condition to the prediction of the final postconstruction settlement.

3. Time-Extended Loading Test Based Assessment System

The proposed time-extended loading test based assessment system is a two-phase estimation approach. By using the field measurement data from TEL test, the postconstruction settlement can be estimated first by using the hyperbolic curve fitting method (final residual settlement). Then, a probabilistic model is built as a bidirectional mapping between the final residual settlement and the true postconstruction settlement. By using the proposed two-phase estimation process, the construction condition difference impact on the postconstruction settlement has been considered by the first phase, hyperbolic curve fitting process. Hence, the probabilistic approach in the second phase acts as a general model without considering the construction condition differences.

3.1. Assessment Indexes of Time-Extended Loading Test. The primary objective of this section is to develop the assessment indexes for evaluating the final postconstruction settlement implicitly. With the consideration of conventional field testing results and the cushion behaviors in practice [34, 35], the hyperbola is selected for representing the relationship between settlement $S(t)$ and time $t$ during the TEL test. Mathematically, we have

$$S(t) = S(t_0) + \frac{t - t_0}{a + (t - t_0)b}$$

Formula (1) can be rewritten as

$$\frac{\Delta t}{\Delta S} = \frac{t - t_0}{S(t) - S(t_0)} = a + (t - t_0)b$$

where $t$ is the cumulative time; $t_0$ is the start time of the TEL test; $S(t_0)$ is the settlement after the static loading test; $S(t)$ is the cumulative settlement at time $t$; $a$ and $b$ are the linear regression results computed from the TEL test to represent the relationship between $\Delta t/\Delta S \sim \Delta t$ after $t_0$.

To obtain the final residual settlement, we have

$$S_{rf} = \lim_{t \to \infty} (S_r(t)) = \lim_{t \to \infty} (S(t) - S(t_0))$$

$$= \lim_{t \to \infty} \frac{t - t_0}{a + (t - t_0)b} = \frac{1}{b}$$

where $S_{rf}$ is the final residual settlement after the TEL test; $S_r(t)$ is the residual settlement.
### Table 2: The field test conditions.

<table>
<thead>
<tr>
<th>Section</th>
<th>Pile type</th>
<th>Pile diameter [m]</th>
<th>Pile length [m]</th>
<th>Pile spacing [m]</th>
<th>Bearing capacity [kPa]</th>
<th>Plate diameter [m]</th>
<th>Plate area [m²]</th>
<th>The design maximum loading value [kPa]</th>
<th>Maximum load[kN]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>cement mixing pile</td>
<td>0.5</td>
<td>13</td>
<td>1.2</td>
<td>120</td>
<td>1.26</td>
<td>1.25</td>
<td>240</td>
<td>300.00</td>
</tr>
<tr>
<td>2</td>
<td>CFG pile I</td>
<td>0.4</td>
<td>20</td>
<td>1.8</td>
<td>310</td>
<td>1.89</td>
<td>2.81</td>
<td>465</td>
<td>1306.65</td>
</tr>
<tr>
<td>3</td>
<td>CFG pile II</td>
<td>0.5</td>
<td>12</td>
<td>2.0</td>
<td>280</td>
<td>2.10</td>
<td>3.46</td>
<td>420</td>
<td>1453.20</td>
</tr>
</tbody>
</table>

### Table 3: The selected test results with observation time.

<table>
<thead>
<tr>
<th>Section</th>
<th>t [h]</th>
<th>S [mm]</th>
<th>t [h]</th>
<th>S [mm]</th>
<th>t [h]</th>
<th>S [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>11.0</td>
<td>10.57</td>
<td>15.0</td>
<td>10.02</td>
<td>29.0</td>
<td>48.13</td>
</tr>
<tr>
<td>2</td>
<td>26.0</td>
<td>11.40</td>
<td>18.5</td>
<td>11.27</td>
<td>43.0</td>
<td>56.18</td>
</tr>
<tr>
<td>3</td>
<td>43.0</td>
<td>12.09</td>
<td>28.5</td>
<td>12.04</td>
<td>58.0</td>
<td>58.49</td>
</tr>
<tr>
<td></td>
<td>48.0</td>
<td>12.33</td>
<td>35.0</td>
<td>12.21</td>
<td>61.0</td>
<td>59.71</td>
</tr>
<tr>
<td></td>
<td>59.0</td>
<td>12.63</td>
<td>45.0</td>
<td>12.35</td>
<td>67.0</td>
<td>60.87</td>
</tr>
</tbody>
</table>

Meanwhile, the settlement rate $V_s(t)$ can be obtained from the formula (1) by taking the derivative with respect to the time $t$ and we have

$$V_s(t) = \frac{dS(t)}{dt} = \frac{a}{a + (t - t_0) b}$$

(4)

When $t$ equals $t_0$, the initial settlement rate $V_s(t_0)$ is $1/a$.

Three field test results are analyzed in this subsection as examples for the illustration of the calculation process of the assessment indexes. The field test conditions are shown in Table 2; the selected test results with observation time are shown in Table 3.

According to (2), let $x = t - t_0$, and $y = \Delta t/\Delta S$. Based on the settlement data obtained from the TEL test, the relationship between $y$ and $x$ can be obtained; see Figure 4. The linear regression results for all three field test results are shown in Table 4. The parameters shown in the relationship between settlement $S(t)$ and time $t$ during the TEL test can be written as

$$S_j(t) = S_j(t_0) + \frac{t - t_0}{a_j + b_j (t - t_0)}$$

(5)

The settlement rate $V_s(t)$ can be calculated from (4) and the $S_j(t)$ can be obtained from (3). The final settlement $S_j(t)|_{t\rightarrow\infty}$ can be obtained from (5). The detailed calculation results can be found in Table 5.

Since the final residual settlement $S_f$ and the settlement rate $V_f(t)$ have directly related to the actual final postconstruction settlement $S_f$. The $S_f$ and $V_f(t)$ can be used as the indicators to estimate the postconstruction settlement for the determination that whether the postconstruction settlement of a composite subgrade satisfies the specification engineering standards. The corresponding mathematic expressions are

$$S_{rf} \leq S_{rt}$$

$$V_s(t_d) \leq V_{rt}$$

(6)

where $t_d$ is the end time of the TEL test; $S_{rt}$ and $V_{rt}$ are the assessment criteria, which usually can be obtained by using the 15-year cumulative settlement requirements of different road sections. Typically, the 15-year cumulative settlement requirements of a bridgehead transition section, a section with structures, and a general road section are 100 mm, 200 mm, and 300 mm; respectively. Different from
have normal distribution to standard normal distribution, and we can use the probability density function (PDF) $f(z)$ of the standard normal distribution

$$f(z) = \frac{1}{\sqrt{2\pi}} e^{-(1/2)z^2}$$

where $z = (s_f - \mu_f) / \sigma_f$.

3.2. Probabilistic Analysis of Time-Extended Loading Test Result. Different from the traditional evaluation system, the statistic properties of the assessment indexes $S_f$ and $V_f(t_0)$ are analyzed in this section. The corresponding assessment criteria $S_{rt}$ and $V_{rt}$ are obtained by using the field monitoring data from 157 road sections and 38 TEL test results which are presented in the previous section. The data preprocess results for the 38 field tests are attached in Supplementary Materials.

3.2.1. Characteristics Analysis for Postconstruction Settlement Distribution. To obtain the assessment criteria, the probabilistic characteristics of the postconstruction settlement should be studied first. According to the predicted postconstruction settlement data $S_f$ shown in Figure 1 and the state of art studies, a lognormal distribution function has been selected to represent the probabilistic distribution of the postconstruction settlement [36]. The detailed steps for obtaining the corresponding statistical parameters in the lognormal distribution function are presented as follows.

According to the assumption, if predicted postconstruction settlement $S_f$ of the composite subgrade follows the lognormal distribution, we have $\ln S_f \sim N(\mu_f, \sigma_f^2)$. Hence, the probability density function (PDF) $f_f(s_f)$ of the postconstruction settlement $S_f$ is

$$f_f(s_f) = \frac{1}{s_f \sqrt{2\pi} \sigma_f} \exp\left(\frac{-(\ln s_f - \mu_f)^2}{2\sigma_f^2}\right)$$

An intermediate variable $z$ is defined to convert the lognormal distribution to standard normal distribution, and we have

$$f(z) = \frac{1}{\sqrt{2\pi}} e^{-(1/2)z^2}$$

where $z = (\ln s_f - \mu_f) / \sigma_f$.

Since $z$ obeys the standard normal distribution, the cumulative distribution function (CDF) $F_f(s_f)$ of the postconstruction settlement $S_f$ can be obtained as

$$F_f(s_f) = \Phi(z) = P(Z \leq z) = \int_{-\infty}^{z} \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}z^2} dz$$

The maximum likelihood estimations for $\mu_f$ and $\sigma_f$ are

$$\hat{\mu}_f = \frac{1}{n} \sum_{i=1}^{n} \ln S_{f,i}$$

$$\hat{\sigma}_f^2 = \frac{1}{n} \sum_{i=1}^{n} \left( \ln S_{f,i} - \frac{1}{n} \sum_{i=1}^{n} \ln S_{f,i} \right)^2$$

where $\hat{\mu}_f$ and $\hat{\sigma}_f^2$ are estimated expectation and variance, respectively; $n$ is the number of the postconstruction data; $S_{f,i}$ is the postconstruction settlement value of the $i^{th}$ sample.

By plugging in the postconstruction settlement data $S_{f,i}$ into (9) and (10), we have $\hat{\mu}_f = 4.64$ and $\hat{\sigma}_f = 0.57$. The calculation result shown above has been validated through nonparametric hypothesis test (Chi-square $\chi^2$ Fit Test). The hypothesis $H_0$ is $F_f(s_f) = F_0(s_f)$, where $F_0(s_f)$ is the CDF of the hypothetical lognormal distribution. To perform Chi-square Fit Test, the sample space (settlement value) has been discretized equally into $K = 17$ subintervals. The length of each intervals is 20 mm. According to the postconstruction settlement data, the minimum and maximum postconstruction settlement in the sample sequence $\{S_{f,i}\}$ are 8.78 mm and 321.15 mm, respectively. Hence the subinterval $[\delta_{k-1}, \delta_k]$ can be represented as $[0, 20), [20, 40), \ldots, [300, 320), [320, +\infty)$. Based on the proposed data classification, the statistical divergence degree $v$ can be calculated as

$$v = \sum_{k=1}^{K} \left( \frac{n_k - n \tilde{p}_k}{n \tilde{p}_k} \right)^2$$

where $n_k$ is the number of data falling to the $k^{th}$ interval $[\delta_{k-1}, \delta_k]$, $n$ is the total number of samples, and $\tilde{p}_k$ is the probability that the settlement $S_f$ belongs to the $k^{th}$ interval $[\delta_{k-1}, \delta_k]$, which can be approximated from the following calculations:

$$\tilde{p}_k = P\{\delta_{k-1} \leq S_f < \delta_k\} = F_f(\delta_k) - F_f(\delta_{k-1})$$

$$\equiv F_0(\delta_k) - F_0(\delta_{k-1})$$

Table 4: The linear regression results for all three field test results.

<table>
<thead>
<tr>
<th>Section</th>
<th>$S_0$/mm</th>
<th>$t_0$/h</th>
<th>$a$</th>
<th>$b$</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10.57</td>
<td>11</td>
<td>14.007</td>
<td>0.3605</td>
<td>0.9918</td>
</tr>
<tr>
<td>2</td>
<td>10.02</td>
<td>15</td>
<td>1.5077</td>
<td>0.3801</td>
<td>0.9999</td>
</tr>
<tr>
<td>3</td>
<td>48.13</td>
<td>29</td>
<td>1.6077</td>
<td>0.0373</td>
<td>0.9630</td>
</tr>
</tbody>
</table>

Table 5: The detailed calculation results.

| Section | $t_0$/h | $V_f(t_0)$ [mm/h] | $V_f(t_0 + 48)$ [mm/h] | $S_f$/mm | $S(t)|_{t \rightarrow \infty}$/mm |
|---------|---------|-------------------|------------------------|---------|-------------------------------|
| 1       | 11      | 0.0710            | 0.0140                 | 2.774   | 13.344                        |
| 2       | 15      | 0.6632            | 0.0039                 | 2.631   | 12.649                        |
| 3       | 29      | 0.6220            | 0.1390                 | 26.810  | 74.940                        |
Based on (12) and the postconstruction settlement data $s_{f,i}$, we have $v = 18.73$. Meanwhile, the degree of freedom $f$ is $K - R - 1 = 14$ where $R$ is the number of unknown parameters. According to the Chi-square distribution table, we have $\chi^2_{0.05}(14) = 17.117 \leq \nu \leq \chi^2_{0.10}(14) = 21.064$, which means the possibility that the distribution of the postconstruction settlement $S_f$ which obeys the estimated lognormal distribution is larger than 90%.

Therefore, the probability density distribution of the postconstruction settlement $S_f$ obeys the lognormal distribution with the parameters that $\hat{\mu}_f = 4.64$ and $\hat{\sigma}_f = 0.57$.

3.2.2. Analysis of Characteristics of Final Residual Settlement Distribution. Based on the TEL test measurements and the corresponding calculation results shown in the previous section, the static load test settlement $S(t_0)$ and the final residual settlement $S_{rf}$ of the 38 different piles under different test conditions are plotted in Figure 5.

According to Figure 5, the maximum settlement in the static load test and the maximum residual settlement in the TEL test are 95.32 mm and 38.76 mm, respectively (no. 24). The minimum initial settlement and final residual settlement are 3.8 mm and 0.299 mm, respectively (no. 1). The maximum likelihood estimations for $\alpha_f$ and $\beta_f$ are calculated and we have $\alpha_f = 0.805$ and the scale parameter $\beta_f = 10.05$. Hence, the assumption is not satisfied since $\alpha$ is smaller than 1. As a result, the PDF of the final residual settlement $S_f$ does not obey the gamma ($\Gamma$) distribution.

(2) Gamma ($\Gamma$) Distribution. We can also assume the PDF of the final residual settlement $S_f$ follows gamma ($\Gamma$) distribution and the shape parameter is greater than 1, namely $S_f \sim \Gamma(\alpha_f, \beta_f)$. According to [37], the shape and scale parameters $\alpha_f$ and $\beta_f$ can be calculated and we have $\alpha_f = 0.805$ and the scale parameter $\beta_f = 10.05$. Hence, the assumption is not satisfied since $\alpha$ is smaller than 1. As a result, the PDF of the final residual settlement $S_f$ does not obey the gamma ($\Gamma$) distribution.

(3) Inverse Gamma ($\Gamma^{-1}$) Distribution. According to [38], the PDF of the final residual settlement $S_f$ may follow an inverse gamma ($\Gamma^{-1}$) distribution with a shape parameter greater than 1, yielding

$$\frac{1}{S_{rf}} \sim \Gamma^{-1}(\alpha_r, \beta_r)$$

Then the PDF and CDF of $S_f$ can be represented as

$$f_r(s_f) = \frac{\beta_r^\alpha_r}{\Gamma(\alpha_r)} s_f^{-\alpha_r-1} e^{-\beta_r s_f}$$

$$F_r(s_f) = \int_0^{s_f} f_r(x) dx$$

The maximum likelihood estimations for $\alpha_r$ and $\beta_r$ are

$$\frac{\hat{\beta}_r}{\bar{\alpha}_r - 1} = \frac{1}{n} \sum_{i=1}^{n} S_{rf,i}$$

$$\frac{\hat{\alpha}_r^2}{(\bar{\alpha}_r - 1)^2 (\bar{\alpha}_r - 1)} = \frac{1}{n} \sum_{i=1}^{n} \left( S_{rf,i} - \frac{1}{n} \sum_{i=1}^{n} S_{rf,i} \right)$$

where $\bar{\alpha}_r$ and $\hat{\beta}_r$ are the estimated statistical parameter of the inverse $\Gamma$ distribution; $S_{rf,i}$ is the final residual settlement of sample $i$. Based on field measurements, one can obtain $\bar{\alpha}_r = 2.805$ and $\hat{\beta}_r = 14.601$.

The cumulative probability function of the final residual settlement $S_f$ is

$$F_r(s_f) = \Phi(z) = P(Z \leq z) = \int_{-\infty}^{z} \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}z^2} dz$$

Similarly, the Chi-square $\chi^2$ Fit Test has been used to validate the results. The hypothesis $H_1$ is $F_r(s_f) = F_0(s_f)$, where $F_r(s_f)$ is the cumulative lognormal probability function. Since the largest final residual settlement is 38.76 mm and the smallest $S_f$ is 0.299 mm, the sample space has been discretized unevenly into $K = 7$ subintervals. The subinterval $[\delta_k, \delta_{k+1})$ are $[0,2), [2,3), [3,5), [5,7), [7,11), [11,23), [23, +\infty)$. According to (12), the statistical divergence degree $v$ is 5.547. The degree of freedom $f$ is $K - R - 1 = 4$ where $R$ is the number of unknown parameters. According to the Chi-square distribution table, we have $\chi^2_{0.05}(4) = 5.858 \leq v \leq \chi^2_{0.10}(4) = 7.779$ meaning the possibility of the hypothesis $H_1$ is larger than 90%.

\[\text{Figure 5: Final residual settlement } S_f \text{ and settlement } S(t_0) \text{ in static load test.}\]
To validate the calculated parameters, the hypothesis $H_2$ is $F_f(s_f) = F_{S_f}(s_f)$, where $F_{S_f}(s_f)$ is a CDF of inverse gamma distribution function with parameter $\hat{\alpha}$ and $\hat{\beta}$. Similarly, sample space has been discretized unevenly into $K = 8$ subintervals: $[0, 3), [3, 4), [4, 5), [5, 7), [7, 9), [9, 12), [12, 23), [23, +\infty)$. The divergence degree $v$ is 22.38. Based on the $\chi^2$ distribution table, we have $v \geq \chi^2_{0.005}(5) = 16.750$ which means the possibility of the hypothesis $H_2$ is larger than 99.5%.

According to the Chi-square Fit Test results shown in the previous section, the PDF of the final residual settlement $S_{rf}$ follows the lognormal distribution with the parameters $\hat{\mu} = 1.57$ and $\hat{\sigma} = 1.07$ or follows the inverse $\Gamma$ distribution with the shape parameter $\hat{\alpha}_r = 2.805$ and the scale parameter $\hat{\beta}_r = 14.601$.

### 3.3. Assessment Criteria

#### 3.3.1. Assessment Criterion Calculation

Based on the analysis in the previous section, the postconstruction settlement $S_{rf}$ is positively correlated with the final residual settlement $S_{rf}$, and the relationship between $S_{rf}$ and $S_{rf}$ can be generalized to the probabilistic space. Probabilistically, we have

$$F_f(S_{rf}) = F_r(S_{rf})$$

(21)

where $F_f$ is the assessment criterion for the postconstruction settlement. Namely, the probability that the postconstruction settlement is smaller than its assessment criterion $S_{rf}$ is equal to the probability that the final residual settlement is smaller than its assessment criterion $S_{rf}$. Based on this relationship, the assessment criterion value of the final residual settlement can be obtained by inverse calculation, yielding

$$S_{rf} = F_r^{-1}(F_f(S_{rf}))$$

(22)

where $F_r^{-1}(\cdot)$ is the inverse function of the CDF $F_r(S_{rf})$. It is worth pointing out that (21) can also be used to predict the postconstruction settlement.

When the allowable postconstruction settlement $S_a$ of transitional bridge sections, structural sections, and general sections are less than 100mm, 200mm, and 300mm, the corresponding probability $F_f(S_a)$ can be obtained from the standard Gaussian distribution table. Based on the probability value, the corresponding $S_{rf}$ can be obtained by using (15) and (18). Hence, the assessment criterion relationships between the final residual settlement and the postconstruction settlement are obtained; see Table 6.

Based on the similar idea, the assessment criterion for the settlement rate can be obtained. To calculate $V_{rt}$ from (4), the CDF of the parameter $a$ is necessary. The experimental cumulative distribution function of the parameter $a = 1/V_r(t_d)$ is plotted in Figure 6.

The exponential function is used to fit the experimental CDF curve of the parameter $a$, yielding

$$F_a(a) = 1 - 1.87e^{-a/4.36}$$

(23)

Similar to (22), we have

$$a_r = F_a^{-1}(F_a(S_{rt}))$$

(24)

where $F_a^{-1}(\cdot)$ is the inverse function of the CDF $F_a(a)$; $a_r$ is the assessment criterion for the parameter $a$. Based on the calculation results shown in Table 6 and (24), (3), and (4), the assessment criterion for the settlement rate $V_r(t_d)$ in the TEL test can be obtained; see Table 7.

It is worth pointing out that the purpose of using two assessment indexes is to enhance the reliability of the assessment results.

### 4. Example Analysis and Discussion

To validate the proposed assessment indexes and criteria, three representative experiment examples are selected and discussed in the following paragraphs.

#### 4.1. Example Analysis

Three road sections with relatively complete settlement measurements were selected and presented in this section. The specific design and construction parameters are concluded in Table 8. The settlement measurements collected during the TEL test are presented in Table 9.
Table 7: Settlement rate criteria $V_{rt}$.

<table>
<thead>
<tr>
<th>Postconstruction settlement [mm]</th>
<th>$V_r(t_d)$ [mm/h]</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>Lognormal distribution 0.021</td>
</tr>
<tr>
<td>200</td>
<td>Inverse $\Gamma$-distribution 0.028</td>
</tr>
<tr>
<td>300</td>
<td>0.048 0.046 0.050</td>
</tr>
</tbody>
</table>

Table 8: Construction parameters for selected subgrade sections.

<table>
<thead>
<tr>
<th>No.</th>
<th>Pile type</th>
<th>Pile diameter [m]</th>
<th>Pile length [m]</th>
<th>spacing [m]</th>
<th>Design Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cement mixing pile</td>
<td>0.5</td>
<td>13</td>
<td>1.2</td>
<td>240</td>
</tr>
<tr>
<td>2</td>
<td>CFG pile</td>
<td>0.4</td>
<td>12</td>
<td>2.0</td>
<td>280</td>
</tr>
<tr>
<td>3</td>
<td>Tube pile</td>
<td>0.3</td>
<td>22</td>
<td>2.6</td>
<td>310</td>
</tr>
</tbody>
</table>

Table 9: Experiment data in time-extended loading test.

<table>
<thead>
<tr>
<th>No.</th>
<th>Total test time [h]</th>
<th>Total settlement before loading [mm]</th>
<th>Total settlement after loading [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>59</td>
<td>10.57</td>
<td>12.63</td>
</tr>
<tr>
<td>2</td>
<td>67</td>
<td>48.13</td>
<td>55.71</td>
</tr>
<tr>
<td>3</td>
<td>62</td>
<td>26.17</td>
<td>30.63</td>
</tr>
</tbody>
</table>

No. 1 and no. 2 road sections were completed and opened to traffic in July 2015; no. 3 road section was completed and opened to traffic in December 2016. The monitoring frequencies of the postconstruction settlement are shown in Table 10. The postconstruction settlement data are shown in Figure 7.

The final residual settlements in the TEL test for three target subgrade sections are collected and shown in Table 11. Meanwhile, the 15-year postconstruction settlement calculated by using hyperbolic curve fitting method and probabilistic methods presented in this paper is given in Table 11. The corresponding prediction errors are shown in Table 12.

According to calculation results from Tables 6, 7, 11, and 12, the lognormal distribution evaluation result has better accuracy than inverse $\Gamma$-distribution when the final residual settlement is smaller than 4.5 mm or larger than 13.3 mm. The inverse $\Gamma$-distribution prediction has better results when the final residual settlement is smaller than 13.3 mm or larger than 4.5 mm. Hence, the construction quality can be evaluated by using the proposed novel assessment method.

In Assessment Indexes Calculation section, the first two road sections, namely, the field tests of the composite cement subgrade of the cement mixing pile and the CFG pile composite subgrade I, satisfied the proposed assessment criteria for both $S_r$ and $V_r(t_d)$. On the contrary, the field test results for the CFG pile composite subgrade II did not meet the proposed criteria. Based on this evaluation, specific remedial actions have been implemented including grouting, compaction, and prolonged preloading. Because of the probability based assessment indexes and the corresponding remedy actions, this road section has operated three years and no significant postconstruction settlement has been found.

5. Conclusion

A novel supplementary test, time-extended loading test, is proposed in this paper for minimizing the construction condition impact on the settlement estimation and increasing the accuracy of the prediction. The corresponding probabilistic model is built for establishing the TEL based assessment system. Compared with the existing estimation methods, the proposed TEL method only relies on the field test data.
of the first 48-hour measurements. Also, the corresponding probabilistic model further improves the accuracy of the classic hyperbolic curve fitting method by mapping the final residual settlement to the postconstruction settlement. Hence, the proposed method can identify the quality of road construction in a very early stage compared with other existing methods. Four major conclusions are listed as follows.

1. The settlement and settlement rate in the time-extended loading test can be obtained by using a hyperbola model. The final residual settlement and the settlement rate after 48 h can be used as the assessment indexes for predicting the final postconstruction settlement.
2. According to our statistical analysis results, the final residual settlement less than 4.5 mm or greater than 13.3 mm obeys the lognormal distribution. The final residual settlement greater than 4.5 mm and less than 13.3 mm follows the inverse gamma distribution.
3. The assessment criteria for the final residual settlement of the bridge-to-bridge transitional section, structural section, and general section corresponding are 4.5 mm, 13.3 mm, and 35.41 mm. The corresponding 48 h settlement rate criteria are 0.021 mm/h, 0.046 mm/h, and 0.055 mm/h.
4. For the pile-soil composite subgrade that does not satisfy the proposed assessment criteria, follow-up remedial measures, such as grouting, compaction, and prolonged preloading, should be applied in the road section based on the actual situation. According to the field experimental results, the follow-up remedial measures help to avoid the occurrences of the severe postconstruction settlements.

Data Availability

The data used to support the findings of this study are included within the supplementary information file (available here).

Disclosure

This work is an original one conducted at Hohai University.

Conflicts of Interest

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

Authors’ Contributions

All the authors have contributed to and approved this paper.

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Supplementary Materials

The 38 field test data during the TEL test are shown in Table A. (Supplementary Materials)

References


