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Research Article

A Prediction Method for Postconstruction Settlement of Pile-Soil Composite Subgrade Based on Fuzzy Comprehensive Evaluation

Hao Shan ,[1] Guanghui Jiang,[2] Yajing Chang,[2] Junli Cheng,[2] Baoning Hong,[3] and Shengcheng Wang[1]

[1]*School of Civil Engineering, Xuzhou University of Technology, Xuzhou 221018, China*
[2]*CSCEC Road and Bridge Group CO.,LTD, Shijiazhuang 050001, China*
[3]*Key Laboratory of Ministry of Education for Geomechanics and Embankment Engineering, Hohai University, Nanjing 210098, China*

Correspondence should be addressed to Hao Shan; shanhao@xzit.edu.cn

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This paper presents a postconstruction settlement prediction method for pile-soil composite subgrade based on the multilevel fuzzy comprehensive evaluation principle. In this method, the variation range of postconstruction settlement can be obtained from a simple calculation based on the basic data of actual engineering. Firstly, according to the characteristics of influencing factors in the construction of soft soil subgrade, the evaluation index set and two-level factor index sets were selected. The grading standards of the evaluation index and factor index were determined according to the allowable value of the standard and the numerical simulation results. Secondly, each factor index was standardized, and the normal distribution function in the form of exponential was used to construct the standard membership function for the first and second factor indexes. Finally, the comprehensive evaluation matrix of postconstruction settlement of composite subgrade was constructed based on the entropy weight method. The variation range of postconstruction settlement was predicted by the principle of maximum membership. The example analysis shows that the predicted results of the prediction method and the field measurement method are in good agreement, indicating that the proposed method can realize the postconstruction settlement prediction of composite subgrade, and the results are more accurate and more instructive.

1. Introduction

The postconstruction settlement of the composite subgrade of expressways has always been concerned by both academia and industry, especially in some special sections, such as bridge head transition sections and the sections containing structures [1, 2]. Higher requirements are put forward for the postconstruction settlement of subgrade in these sections. So people often adopt the foundation treatment method of pile-soil composite subgrade. Compared with other foundation treatment methods, pile-soil composite subgrade has certain advantages in improving the stability of subgrade and reducing settlement. However, there are still some large postconstruction settlements in the treatment section of pile-soil composite subgrade, such as car jump at the bridge head. Many scholars and engineers have carried out much useful work in the prediction of postconstruction settlements by means of theoretical analysis [3], numerical simulation [4], and on-site observation data fitting [5, 6]. Previous related works on postconstruction settlement prediction are discussed and tabulated in Table 1.

In this paper, based on a large amount of postconstruction settlement field test data, a new prediction method of postconstruction settlement of composite subgrade is proposed using the multilevel fuzzy comprehensive evaluation method. This method calculates the variation interval of postconstruction settlement through a simple calculation by only considering the basic data from actual projects. The calculation results are beneficial to the optimization of design and improvement of construction

Table 1: Previous related works on foundation settlement.

Authors	Data set size	Method	Reliable condition
Omar et al. [7]	Footing width, effective unit weight, and SPT blow count	Artificial neural network	Shallow foundation on granular soils
Wang et al. [8]	Soil properties and parameters related to the pile, such as pile spacing, pile length, and cap width	A calculation model for predicting the additional stresses in the composite foundation soil and the layerwise summation method	Composite foundation with sparse prestressed tubular concrete (PTC) capped-piles under embankment
Meng et al. [9]	The compression parameters of underlying soils related to soil disturbance degree	The layerwise summation method	Ground and tunnel
Eid et al. [3]	Pile-subgrade stiffness ratios for piled foundations on nonhomogeneous media	Three-dimensional finite-element (FE) analysis	The elastic settlement of piled foundations resting on rock
Hong et al. [2]	The time-extended loading residual settlement and settlement rate calculated from the field test data	An improved static loading test method, time-extended loading test	Pile-soil composite subgrade
Kermani et al. [10]	Rockfill modulus and rock strength	A novel approach considering the dam's deformation behavior during construction	Concrete face rockfill dams
Wang et al. [5]	Three appropriate points for the measured settlement curve in the prediction samples	A three-point hyperbolic combination model	Subgrade filled with construction and demolition waste
Cai et al. [11]	The calculated dynamic stresses	The equivalent timeline model combined with the cyclic strain accumulation model	The long-term settlements of roads on soft soil under cyclic traffic loadings
Mohammed et al. [12]	The width of footing, pressure of footing, geometry of footing, count of SPT blow, and ratio of footing embedment	Machine learning models	Settlement of shallow foundation over cohesion soil properties
Tang et al. [13]	The observation data of settlement during construction	The Hushino model, hyperbolic curve method, and exponential curve method	Foundation after construction
Ding [14] and Zhang et al. [15]	The design parameters	Numerical simulation approach	Pile-soil composite subgrade

quality. In the establishment process of this method, it is difficult to calculate weight and membership degree accurately, and there are many factors involved. Hence, the entropy weight method, standardized membership function, and two-level evaluation system are introduced. In this way, not only the calculation accuracy is improved but also the index of influencing factors involved in the comprehensive evaluation in each level is reduced, which is more convenient for practical applications.

2. Need for Research

In recent years, artificial intelligence technology has been developed rapidly, but at present, artificial intelligence technology still has some shortcomings and limitations [16–18]. Firstly, it needs more data and data support to build the model. When the data are insufficient, the error is often large. Secondly, sometimes, in the modeling process, some engineering features or states need to be represented by numbers, which will lead to the loss of information. Finally, the results obtained by the artificial intelligence technology model are usually qualitative indicators, while the quantitative indicators are relatively few and not rigorous enough. However, in addition to the aforementioned disadvantages, artificial intelligence technology also has obvious advantages [19–21]. First of all, it is an important tool for system analysis and will not cut the relationship between influencing factors and results. Secondly, it can solve complex relationships between multiple factors and predict unknown data. Finally, its analysis results are often more concise, easy-to-make decisions.

Considering that the advantages of artificial intelligence technology have a great help to solve complex engineering problems, some artificial intelligence technologies have been widely used in civil engineering. To predict the settlement of rock-socketed piles, Danial et al. [22, 23] presented the development of a hybrid ANN-based model named PSO-ANN (or neuro-swarm) with detailed modeling process and a new model based on gene expression programming (GEP). Li et al. [16] use least squares support vector machines (LSSVMs) based on multipoint measurement to monitor and predict foundation pit displacement. In addition, fuzzy comprehensive evaluation (FCE) method is also a typical artificial intelligence technology; it can better solve the fuzzy but difficult to quantify the problem and is suitable for all kinds of nondeterministic problems. The FCE method has been widely used in mineral [24], environmental [25], slope [26] and other engineering areas [27]. However, its application in postconstruction settlement of composite subgrade has not been reported. As the postconstruction settlement of composite subgrade involves many factors and has obvious randomness, it is meaningful to explore the method of uncertainty and establish a prediction model and a calculation method.

3. Evaluation Index and Influencing Factors

As the postconstruction settlement of composite subgrade can be affected by many factors, a two-level fuzzy comprehensive evaluation system considering the main influencing factors is selected. The evaluation system can make up for the shortcomings of the existing single-level evaluation methods and make the evaluation results more accurate and more instructive [20]. In the two-level fuzzy comprehensive evaluation system, one of our key works is to determine the reasonable evaluation index set and the factor index set of each layer for improving the accuracy and practicability of the prediction method.

3.1. Evaluation Index Set. In the two-level fuzzy comprehensive evaluation system, an evaluation index v is constructed for describing the severity of the postconstruction settlement of the composite subgrade, and we have

$$V = \{v_1, v_2, \ldots, v_m\}, \tag{1}$$

where V is a set that contains all the possible values of the evaluation index v. According to the requirements of the current specification in China, allowable values for the postconstruction settlements of high-quality highways at the bridgehead transition section, structural section, and general road section are 100, 200, and 300 mm, respectively. Therefore, the element vm in the evaluation index set V is obtained based on the postconstruction settlement value. The smaller the postconstruction settlement value, the better the construction quality. In this paper, the evaluation index set contains four values to represents four quality grades (see Table 2.

The space of the postconstruction settlement has been divided into four subsections, and the corresponding normalized classification intervals (w.r.t 400 mm) are also given in Table 1. For the postconstruction settlement larger than 400 mm, 400 mm is applied to the normalization process. Hence, we have a closed range of the postconstruction settlement after the normalization process.

3.2. Influencing Factors Set. Since the postconstruction settlement of CFG pile composite subgrade-based road section involves many influencing factors, a two-level fuzzy comprehensive evaluation model is adopted to tackle the problem: 15 secondary influencing factors are constructed as the leaves of 4 primary influencing factors (geology, pile, cushion, and construction). Mathematically, we have

$$\begin{aligned} &U = \{U_1, U_2, U_3, U_4\},\\ &U_i = \left\{u_{i1}, u_{i2}, \ldots u_{ij}, \ldots, u_{in_i}\right\}, \quad i = 1, 2, 3, 4 \text{ and } j = 1, 2, \ldots, n_i, \end{aligned} \tag{2}$$

where U_i is the primary influencing factor, u_{ij} is the secondary influencing factor, and n_{i} is the number of secondary influencing factors included in U_i.

The factor values of the secondary influencing factors vary with the engineering characteristics. Taking CFG pile composite subgrade in Guangdong Province as an example, this paper discusses the method of determining the secondary influencing factors. According to the collected sample data of a large number of CFG pile composite subgrade engineering projects, existing specification requirements, and on-site survey results collected by the authors, the range of the factor for each secondary influencing factor is provided as follows.

The influencing factors of the geology U_1 consist of compressed soil thickness u_{11}, compression modulus u_{12}, cohesion u_{13}, and internal friction angle u_{14}.

In practical projects, the depth of CFG piles should not exceed 30 m. Otherwise, the quality of composite subgrade is not easy to control. Therefore, the range of compressed soil thickness u_{11} should be 0 to 30 m. The cross-board shear strength of soft soil in Guangdong region is generally 4 to 12 kPa. In the shear strength index, the minimum cohesion $c < 3.2$ kPa, the minimum internal friction angle $\varphi < 2.1^{\circ}$, the porosity ratio is generally greater than 1.0, and the compression coefficient is within 0.5 to 1.0 MPa^{-1}. Therefore, the range of the cohesive force u_{13} is 1 to 15 kPa, the range of the internal friction angle u_{14} is 1° to 15°, and the range of compression modulus u_{12} is 1 to 10 MPa.

The influencing factors of the pile U_2 consist of pile modulus u_{21}, pile length u_{22}, pile diameter u_{23}, and pile spacing u_{24}.

Generally, CFG pile length range u_{22} is 0 to 30 m, the pile diameter u_{23} should be 0.35 to 0.60 m, and the pile spacing u_{24} should be 1.4 to 3.0 m. As the CFG pile design strength range is 5 to 20 MPa, the rounding range in CFG pile compression modulus u_{21} is ranging from 800 to 30,000 MPa.

The influencing factors of the cushion U_3 consist of cushion thickness u_{31}, cushion modulus u_{32}, and cushion internal friction angle u_{33}.

In practical projects, the general thickness of the CFG pile composite subgrade cushion is 0.3 to 0.6 m. Considering the action of the pile top support, the thickness of the cushion u_{31} is in the range of 0 to 0.8 m. As the cushion is mainly medium coarse sand and gravel, the cushion modulus u_{32} ranges from 50 to 250 MPa and the cushion internal friction angle u_{33} ranges from 15° to 60°.

The influencing factors of the construction U_4 consist of filling height u_{41}, filling rate u_{42}, preloading height u_{43}, and preloading time u_{44}.

The filling height of expressways is mainly affected by terrain and routes. Except for a few hill areas, the filling height usually does not exceed 20 m (including the converted thickness of the pavement structure layer). Therefore, the filling height u_{41} ranges from 1 to 20 m. The embankment filling regular loading rate is 20 to 70 mm/d, the loading rate usually is less than 20 mm/d, and the loading rate is greater than 70 mm/d for fast loading. For the convenience of the analysis, the filling rate u_{42} ranges from 5 to 100 mm/d. Surcharge preloading mainly includes under-preloading, equal-preloading, and over-preloading. Under normal circumstances, the overloading height does not exceed 3.0 m, and the preloading time does not exceed 1 year. Therefore, the preloading height range is 0 to 3.0 m, and the preloading time range is 0 to 360 days.

Table 2: Classification standard for postconstruction settlement.

Evaluation index		Postconstruction settlement (mm)	Standard classification interval
v_1	Excellent	[0, 100)	[0, 0.25)
v_2	Good	[100, 200)	[0.25, 0.50)
v_3	Moderate	[200, 300)	[0.50, 0.75)
v_4	Poor	[300, +∞)	[0.75, 1)

4. Factor Grading Standard of Secondary Influencing Factors

By analysing a large number of engineering samples, the finite-element numerical software can be used to calculate the single-factor influence of the representative engineering example of composite subgrade. To determine the factor grading standard of all the secondary influencing factors, the influence of the individual factor was analysed separately by taking five to six values within its range. Taking CFG pile composite subgrade as an example, Plaxis finite-element numerical software can be used to analyse the law of single-factor influence. The detailed simplified processing, calculation method, and calculation process, as well as reliability demonstration will not be discussed due to the limitation of space. The specific method to determine the grading standard of the secondary influencing factors is as follows.

4.1. Quantification of Influence of Individual Factors. According to the FEM simulation results, three categories can be concluded to describe the relationship between the postconstruction settlement changes and the secondary influencing factors.

This first category is named as positive attribute factor u_{ij}^{+}. As the factor u_{ij}^{+} increases, the postconstruction settlement value increases and the evaluation grade decreases. According to the simulation studies, compressed soil thickness u_{11}, pile spacing u_{24}, filling height u_{41}, and filling rate u_{42} belong to this category.

The second category is named as negative attribute factor u_{ij}^{-}. As the factor value increases, the postconstruction settlement value decreases and the evaluation grade increases. Compression modulus u_{12}, cohesion u_{13}, pile modulus u_{21}, pile length u_{22}, pile diameter u_{23}, cushion thickness u_{31}, cushion modulus u_{32}, internal friction angle of cushion u_{33}, preloading height u_{32}, and preloading time u_{33} belong to this category.

The third category is named as zero attribute factor. As the factor value increases, the postconstruction settlement value does not change or changes little. The internal friction angle of subgrade soil u_{14} belongs to this category.

For analysing the physical quantities with different units, a normalization process is implemented to both positive and negative attribute factors (zero-attribute factor is considered as the positive attribute factor in this paper). The normalization formulas for both positive and negative attribute factors are as follows:

$$q_{ij} = \frac{\max\left(u_{ij}^{+}\right) - u_{ij}^{+}}{\max\left(u_{ij}^{+}\right) - \min\left(u_{ij}^{+}\right)}. \tag{3}$$

$$q_{ij} = \frac{u_{ij}^{-} - \min\left(u_{ij}^{-}\right)}{\max\left(u_{ij}^{-}\right) - \min\left(u_{ij}^{-}\right)}. \tag{4}$$

According to formula (3), the normalized positive attribute factors have a negative correlation with the postconstruction settlement and a positive correlation with the evaluation grade.

The relationships between the postconstruction settlements and the normalized values of the influencing factors are concluded and shown in Figures 1 to 4.

According to Figures 1 to 4, the contribution of each secondary influencing factor can be obtained, which can be used as the reference for weight distribution in the fuzzy comprehensive evaluation process.

Based on Figure 1, the postconstruction settlement is very sensitive to the compressed soil thickness q_{11} and the compression modulus q_{12}. Compared with q_{11} and q_{12}, the changes of the cohesion q_{13} have a small effect on the postconstruction settlement. The changes of the internal friction angle of subgrade soil do not influence the postconstruction settlement.

Among the influencing factors of the pile, the postconstruction settlement is sensitive to the pile modulus q_{21} and pile length q_{22}. The pile diameter q_{23} has the smallest influence on the postconstruction settlement in Figure 2.

In Figure 3, the changes of the internal friction angle q_{33} and the thickness of the cushion q_{31} have major effects on the postconstruction settlement. In comparison, the influence of the cushion modulus q_{32} is relatively small.

Among the construction-influencing factors, the preloading height q_{43} and preloading time q_{44} have a major effect on the postconstruction settlement, and the effects of the filling height q_{41} and filling rate q_{42} are relatively small.

4.2. Grading Standard. According to the simulation and analysis results shown in Figures 1 to 4, the linear interpolation method is used to determine the relationships between the normalized factors q_{ij} and the postconstruction settlement and we have $q_{ij} = f_{ij}(S_p)$. Where S_p is the postconstruction settlement, f_{ij} ( ) is the linear mapping from postconstruction settlement to normalized influencing factor q_{ij}. Based on the derived linear relationships f_{ij} ( ), the values of the normalized factors q_{ij} can be calculated when S_p equals 100, 200, and 300 mm. As a result, the corresponding u_{ij} can be obtained, and the grading standard can be

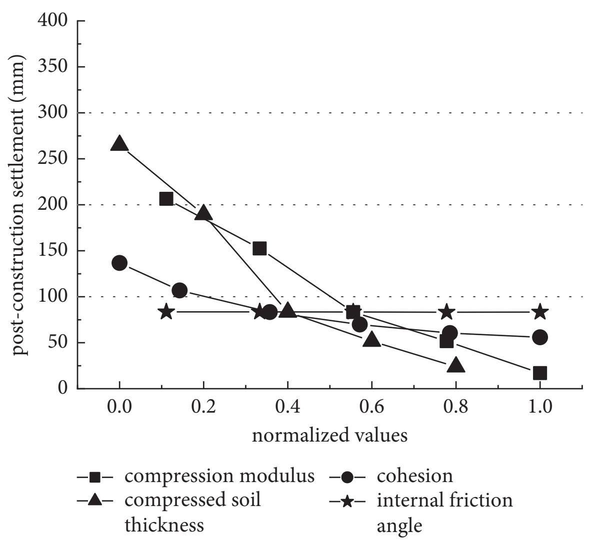

FIGURE 1: Effects of geological factors on postconstruction settlement.

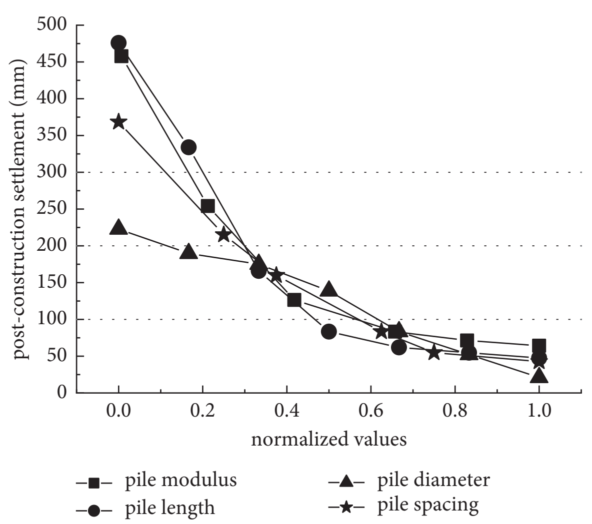

FIGURE 2: Effects of piles geological factors on postconstruction settlement.

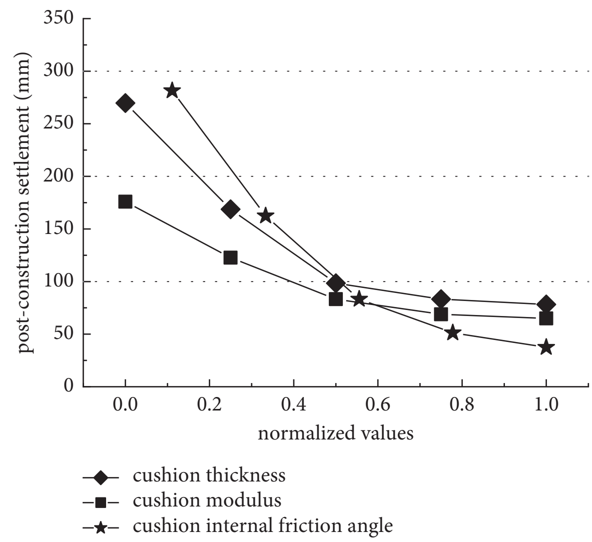

FIGURE 3: Effects of cushion factors on postconstruction settlement.

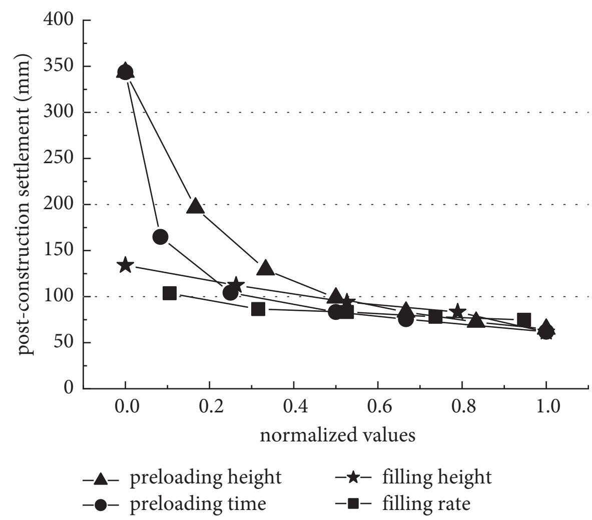

FIGURE 4: Effects of construction factors on postconstruction settlement.

determined. For particular influencing factors, the post-construction settlement is smaller than 300 mm when $q_{ij} = 0$. At the same time, we need to consider all the situations when $S_p > 100$ mm. Hence, additional grading procedures are added as follows:

(a) $S_p \in [200, 300)$: the linear interpolation method is used to determine the q_{ij} values when the settlement equals to 100 and 200 mm. The q_{ij} value for $S_p = 300$ mm is equal to $0.5f_{ij}$ (200). With the q_{ij} for $S_p = 100$, 200, and 300 mm, the corresponding u_{ij} can be determined, and grading standard can be obtained.

(b) $S_p \in [100, 200)$: the linear interpolation method is used to determine the q_{ij} value when the settlement is 100 mm. The q_{ij} value for $S_p = 200$ mm is equal to $0.5f_{ij}$ (100) and the q_{ij} value for $S_p = 300$ mm is equal to $0.25f_{ij}$ (100). With q_{ij} for $S_p = 100$, 200, and 300 mm, the corresponding u_{ij} can be determined, and grading standard can be obtained.

The change of friction angle in the subgrade soil does not affect the postconstruction settlement S_p. Therefore, the entire range of internal friction angle belongs to the grade v_1.

Classification standard of all the secondary influencing factors is shown in Tables 3 and 4.

5. Membership Functions and Weights

Based on the sensitivity analysis in the previous section and the classification standard of influencing factors in Tables 2 and 3, the membership functions and weights in the fuzzy comprehensive evaluation can be determined. As many factors are affecting the postconstruction settlement of CFG pile composite subgrade, a standardized membership

Table 3: Initial conditions and classification standard of geological and pile secondary influencing factors.

Index		Geological influencing factors U_1			Pile influencing factors U_2			
		u_{11} (m)	u_{12} (MPa)	u_{13} (kPa)	u_{21} (MPa)	u_{22} (m)	u_{23} (m)	u_{24} (m)
Initial condition		18	6	6	2 × 104	15	0.5	2.0
Classification standard	v_1	0~18.94	5.52~10.00	3.87~15.00	17,288.90~30,000	13.99~30.00	0.48~0.60	1.40~2.09
	v_2	18.94~24.84	2.24~5.52	2.43~3.86	9543.25~17,288.90	8.99~13.99	0.39~0.48	2.09~2.55
	v_3	24.84~27.42	1.62~2.24	1.71~2.43	5649.22~9543.25	6.01~8.99	0.34~0.39	2.55~2.82
	v_4	27.42~30.00	1.00~1.62	1.00~1.71	800.00~5649.22	0~6.01	0.30~0.34	2.82~3.00

Table 4: Initial conditions and classification standard of cushion and construction secondary influencing factors.

Index		Cushion influencing factors U_3			Construction influencing factors U_4			
		u_{31} (m)	u_{32} (MPa)	u_{33} (°)	u_{41} (m)	u_{42} (mm/d)	u_{43} (m)	u_{44} (d)
Initial condition		0.6	150	40	6	50	2.0	180
Classification standard	v_1	0.40~0.80	128.81~250	32.89~60.00	1.00~11.61	5.00~85.76	1.48~3.00	108.30~360
	v_2	0.14~0.40	89.41~128.81	21.85~32.89	11.61~15.80	85.76~92.88	0.49~1.48	24.10~108.30
	v_3	0.07~0.14	69.70~89.41	18.42~21.85	15.80~17.90	92.88~96.44	0.15~0.49	7.32~24.10
	v_4	0~0.07	50.00~69.70	15.00~18.42	17.90~20.00	96.44~100.00	0~0.15	0~7.32

function is used to describe the influence of each secondary influencing factor. The entropy weight method is used to determine the weights of the primary and secondary influencing factors.

5.1. Standardized Membership Functions. Normal membership function: the commonly used membership functions in geotechnical engineering area are normal-type functions, triangular fuzzy functions, trapezoidal functions, and ridge-type functions [28]. The parameter membership function that in geotechnical engineering should adopt an exponential normal distribution function was suggested [29]. Therefore, the membership function [30] of the structural influencing factor u_{ij} on the evaluation index is as follows:

$$f_k(u_{ij}) = \exp\left[-\left(\frac{u_{ij} - a_{ij}^{(k)}}{c_{ij}^{k}}\right)^2\right], \tag{5}$$

where k is the evaluation index of u_{ij} and $a_{ij}^{(k)}$ and $c_{ij}^{(k)}$ are constants, satisfying $a_{ij}^{(k)} > 0$ and $c_{ij}^{(k)} > 0$.

Standardization of membership functions: to give a standardized membership function, the classification interval of the secondary influencing factor is linearly converted into a classification standard interval with the same size as the evaluation index. According to the level k to which u_{ij} belongs, the positive and negative attribute factors have been normalized separately. After standardized treatment of influencing factors, the classification standards of each factor are consistent with the classification ranges of the postconstruction settlement classification standards in Table 1. $a_{ij}^{(k)}$ and $c_{ij}^{(k)}$ can be calculated using the upper and lower boundaries of the classification intervals of each factor classification standard. For the evaluation index level $v_1 \sim v_4$, the normal distribution membership function in the form of the normalized index is

$$r_{ij}^{(1)} = \begin{cases} 1 & y_{ij} < 0.125 \\ \exp\left[-\left(\dfrac{y_{ij} - 0.125}{0.15014}\right)^2\right] & 0.125 \le y_{ij} < 0.25 \\ 1 - \exp\left[-\left(\dfrac{y_{ij} - 0.375}{0.15014}\right)^2\right] & 0.25 \le y_{ij} < 0.375 \\ 0 & 0.375 \le y_{ij} < 1 \end{cases}, \tag{6}$$

$$r_{ij}^{(2)} = \begin{cases} 0 & y_{ij} < 0.125 \vee y_{ij} \ge 0.625 \\ 1 - \exp\left[-\left(\dfrac{y_{ij} - 0.125}{0.15014}\right)^2\right] & 0.125 \le y_{ij} < 0.25 \\ \exp\left[-\left(\dfrac{y_{ij} - 0.375}{0.15014}\right)^2\right] & 0.25 \le y_{ij} < 0.50 \\ 1 - \exp\left[-\left(\dfrac{y_{ij} - 0.625}{0.15014}\right)^2\right] & 0.50 \le y_{ij} < 0.625 \end{cases}, \tag{7}$$

$$r_{ij}^{(3)} = \begin{cases} 0 & y_{ij} < 0.375 \vee y_{ij} \ge 0.875 \\ 1 - \exp\left[-\left(\dfrac{y_{ij} - 0.375}{0.15014}\right)^2\right] & 0.375 \le y_{ij} < 0.50 \\ \exp\left[-\left(\dfrac{y_{ij} - 0.625}{0.15014}\right)^2\right] & 0.50 \le y_{ij} < 0.75 \\ 1 - \exp\left[-\left(\dfrac{y_{ij} - 0.875}{0.15014}\right)^2\right] & 0.75 \le y_{ij} < 0.875 \end{cases}, \tag{8}$$

$$r_{ij}^{(4)} = \begin{cases} 0 & y_{ij} < 0.625 \\ 1 - \exp\left[-\left(\dfrac{y_{ij} - 0.625}{0.15014}\right)^2\right] & 0.625 \le y_{ij} < 0.75 \\ \exp\left[-\left(\dfrac{y_{ij} - 0.875}{0.15014}\right)^2\right] & 0.75 \le y_{ij} < 0.875 \\ 1 & y_{ij} \ge 0.875 \end{cases}, \tag{9}$$

where y_{ij} is the normalized value of the influencing factor; $r_{ij}^{(k)}$ is the standard membership value of each influencing factor, and $k = 1$, 2, 3, and 4. The membership of each secondary influencing factor can be obtained using formulas (6) to (9). After obtaining the membership value of each secondary influencing factor, a matrix R_i can be constructed:

$$\mathbf{R}_i = \begin{bmatrix} r_{i1}^{(1)} & r_{i1}^{(2)} & r_{i1}^{(3)} & r_{i1}^{(4)} \\ r_{i2}^{(1)} & r_{i2}^{(2)} & r_{i2}^{(3)} & r_{i2}^{(4)} \\ \vdots & \vdots & \vdots & \vdots \\ r_{in_i}^{(1)} & r_{in_i}^{(2)} & r_{in_i}^{(3)} & r_{in_i}^{(4)} \end{bmatrix}. \tag{10}$$

5.2. Weights of Influencing Factors. In the fuzzy comprehensive evaluation of multiple influencing factors, the weight is a measure of the influence of each influencing factor on the evaluation index. The method of determining the weight can generally be divided into subjective empowerment and objective weighting methods. Common subjective empowerment methods have Delphi method, analytic hierarchy process, and statistical method. Common objective weighting methods include entropy weight method, principal component analysis method, and mean square error method. As the subjective empowerment method relies on human factors, such as expert experience which may cause bias on the evaluation results, the entropy weight method in the objective weighting method is used to determine the weight of the influencing factors.

Entropy is a physical quantity that reflects the randomness and disorder of subjects. The weight of each influencing factor can be constructed based on the entropy of each influencing factor [31]. The steps for determining the weights of influencing factors by the entropy weight method are provided as follows [32]:

(1) Collect the influencing factor samples from T projects. The projects are ordered and t is the index of the project.

(2) Calculate the normalization value $y_{ij,t}$ of the secondary influencing factors.

(3) Calculate the ratio $p_{ij,t}$ by

$$p_{ij,t} = \frac{y_{ij,t}}{\sum_{t=1}^{T} y_{ij,t}}. \tag{11}$$

(4) Calculate the entropy E_{ij} of the secondary influencing factor u_{ij} with

$$E_{ij} = -\xi \sum_{t=1}^{T} p_{ij,t} \ln\left(p_{ij,t}\right), \tag{12}$$

where $\xi = 1/\ln(T)$ is a constant related to the number of samples. $p_{ij,t}$ has three requirements:

$$p_{ij,t} \in [0,1], \quad \sum_{t=1}^{T} p_{ij,t} = 1, \quad p_{ij,t}\ln\left(p_{ij,t}\right) = 0|_{p_{ij,t}=0}. \tag{13}$$

The larger E_{ij} is, the smaller the information of U_i contained in u_{ij} is and vice versa.

(5) Calculate the difference coefficient d_{ij} of each secondary influencing factor E_{ij} by

$$d_{ij} = 1 - E_{ij}. \tag{14}$$

And then calculate the weight w_{ij} of u_{ij} w.r.t. U_i. The expression of w_{ij} is

$$w_{ij} = \frac{d_{ij}}{\sum_{j=1}^{n_i} d_{ij}} = \frac{1 - E_{ij}}{\sum_{j=1}^{n_i}\left(1 - E_{ij}\right)} = \frac{1 - E_{ij}}{n_i - \sum_{j=1}^{n_i} E_{ij}}. \tag{15}$$

According to formula (15), a weight vector for the secondary influencing factors can be obtained, we have

$$W_i = \left[w_{i1}, w_{i2}, \ldots, w_{in_i}\right], \tag{16}$$

where all weight factors satisfy $\sum_{j=1}^{n_i} w_{ij} = 1$ naturally.

(6) Use formula (16) to calculate the normalized value $Y_{i,t}$ of the primary influencing factor $U_{i,t}$ for project t, and we have

$$Y_{i,t} = \sum_{j=1}^{n_i} w_{ij} y_{ij,t}. \tag{17}$$

(7) Use the entropy weight method similar to the process from Steps 2 to 5, the weight of the primary influencing factors can be calculated. According to formula (11), the ratio $P_{i,t}$ and entropy E_i of the primary influencing factor $U_{i,t}$ are computed by

$$P_{i,t} = \frac{Y_{i,t}}{\sum_{t=1}^{T} Y_{i,t}}, \quad E_i = -\xi \sum_{t=1}^{T} P_{i,t} \ln\left(P_{i,t}\right), \tag{18}$$

when $P_{i,t} = 0$, $P_{i,t}\ln(P_{i,t}) = 0$. The difference coefficient that defines for the primary influencing factor U_i is

$$D_i = 1 - E_i. \tag{19}$$

The weight of the primary influencing factors on the evaluation indicators is

$$\begin{aligned} w_i &= \frac{D_i}{\sum_{i=1}^{4} D_{ij}} \\ &= \frac{1 - E_i}{\sum_{i=1}^{4} (1 - E_i)} \\ &= \frac{1 - E_i}{4 - \sum_{i=1}^{4} E_i}. \end{aligned} \tag{20}$$

A weight vector of the primary influencing factors can be obtained:

$$W = [w_1, w_2, w_3, w_4], \tag{21}$$

where all weight factors satisfy $\sum_{i=1}^{4} w_i = 1$.

6. Postconstruction Settlement Assessment Method for Two-Level Fuzzy Comprehensive Evaluation

After introducing the evaluation index, the influencing factor grading standard, the standardized membership function, the weight of the influencing factors, and a two-level fuzzy comprehensive evaluation method of the postconstruction settlement of the CFG pile composite subgrade are proposed in this section.

6.1. Evaluation Procedure.

(1) According to the postconstruction settlement requirements of the CFG pile composite subgrade in different road sections and the factors affecting the postconstruction settlement, the evaluation index evaluation set V, the primary influencing factor set U, and the secondary influencing factor set U_i are determined. The secondary influencing factors are the inputs of this model.

(2) Derive the relationship matrix R_i for each primary influencing factors based on formula (10).

(3) Based on formula (16), determine the comprehensive evaluation vector B_i for the primary influencing factor U_i using

$$\begin{aligned} B_i &= W_i \circ R_i \\ &= \left[b_i^{(1)}, b_i^{(2)}, b_i^{(3)}, b_i^{(4)}\right], \end{aligned} \tag{22}$$

where " $\circ$ " is the sign of the composition operator; this paper takes the composition operator as the addition and multiplication operator M (g+), namely,

$$b_i^{(k)} = \sum_{j=1}^{n_i} w_{ij} r_{ij}^{(k)}. \tag{23}$$

(4) Construct the relationship matrix R for the primary influencing factors:

$$\begin{aligned} \mathbf{R} &= \begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \end{bmatrix} \\ &= \begin{bmatrix} b_1^{(1)} & b_1^{(2)} & b_1^{(3)} & b_1^{(4)} \\ b_2^{(1)} & b_2^{(2)} & b_2^{(3)} & b_2^{(4)} \\ b_3^{(1)} & b_3^{(2)} & b_3^{(3)} & b_3^{(4)} \\ b_4^{(1)} & b_4^{(2)} & b_4^{(3)} & b_4^{(4)} \end{bmatrix}. \end{aligned} \tag{24}$$

(5) Calculate the evaluation vector B for the evaluation index by using

$$B = W \circ \mathbf{R} = [b_1, b_2, b_3, b_4], \tag{25}$$

where

$$b_k = \sum_{i=1}^{4} w_i b_i^{(k)}. \tag{26}$$

(6) Determine the evaluation results of the postconstruction settlement based on the value of the element in the evaluation vector B.

6.2. Weights of Factors Affecting Postconstruction Settlement of CFG Pile Composite Subgrade. Taking CFG pile composite subgrade in Guangdong Province as an example, the calculation process and analysis method of the index weight of each layer are described. With the support from the Guangdong Province Transportation Engineering Quality Supervision Station, the authors have collected the design and construction data from 71 different CFG pile composite subgrade road sections in Guangdong Province area. All the CFG pile composite subgrade road sections have operated for 2 to 5 years. Based on the entropy weight method mentioned in the previous section, the weights of the secondary influencing factors are calculated and given in Tables 5 and 6.

According to the secondary weight factor values shown in Tables 5 and 6, the weights of the internal friction angle (2.5%) of the subgrade soil and the filling rate (9.3%) are relatively small, and they have little effect on their corresponding primary influencing factors. The weights of all other secondary influencing factors exceed 20% and smaller than 50%, which is satisfied with our claim that the postconstruction settlement of CFG pile composite subgrade depends on many factors. The weights of all the secondary influencing factors are in consistent with the sensitivity analysis results discussed in the previous section.

Similarly, the weights of the primary influencing factors can be computed. The results are shown in Table 7.

The data in Table 7 show that the weights of the influencing factors of cushion, pile, construction, and geology are reduced in descending order, meaning their

Table 5: Weights of geological and pile secondary influencing factors.

Index	Geological influencing factor U_1				Pile influencing factor U_2			
	u_{11}	u_{12}	u_{13}	u_{14}	u_{21}	u_{22}	u_{23}	u_{24}
Weights (%)	39.1	35.9	22.5	2.5	27.4	24.3	26.9	21.4

Table 6: Weights of cushion and construction secondary influencing factors.

Index	Cushion influencing factor U_3			Construction influencing factor U_4			
	u_{31}	u_{32}	u_{33}	u_{41}	u_{42}	u_{43}	u_{44}
Weights (%)	41.1	21.7	37.2	22.3	9.3	37.4	31.0

Table 7: Weights of primary factor index.

Index	Weights (%)
Geological influencing factor U_1	15.7
Pile influencing factor U_2	29.4
Cushion influencing factor U_3	34.8
Construction influencing factor U_4	20.1

influences on the postconstruction settlement are reduced in turn. For composite subgrade, the cushion plays a role in adjusting the stress ratio of the pile and soil and determines the structural form of the bearing system. The pile is the main bearing part for undertaking the weight of the composite subgrade. Hence, the weight of the geological influencing factor is the smallest (15.7%) among all the primary influencing factors. However, none of the primary influencing factors can be neglected. The calculated weights of the primary influencing factors also indicate that the proposed entropy weight method can be used for analysing the relationships between the primary influencing factors and the postconstruction settlements.

6.3. Example Analysis

6.3.1. Model Inputs. A bridge transition section in Guangdong Province has been selected to validate the proposed evaluation method. The target bridge transition section has CFG pile composite subgrade. The geological conditions and construction information are concluded as follows. The compressed soil thickness u_{11} is 22.6 m, the averaged compression modulus u_{12} is 6450 kPa, the averaged cohesion u_{13} is 9.5 kPa, and the internal friction angle u_{14} is 6.7°. The pile diameter u_{23} is 0.4 m, the pile length u_{22} is 25 m, the pile spacing u_{24} is 2.2 m, and the pile modulus u_{21} is 8.0 GPa. The piles have a plum-type arrangement. The gravel cushion thickness u_{31} is 30 cm, the cushion modulus u_{32} is 100 MPa, and the cushion internal friction angle u_{33} is 35°. The filling height u_{41} is 5.3 m, and the filling rate u_{42} is 80 mm/d. Due to the tight schedule, the preloading process has not been applied in this road section. In this case, the preloading height u_{43} and preloading time u_{44} are 0. The index value and normalized value of secondary influencing factors are shown in Tables 8 and 9.

6.3.2. Postconstruction Settlement Prediction. Based on the information of the target road section, the relationship matrix R_i of each secondary influencing factors can be obtained. Following the process mentioned in the previous section, the relationship matrix R can be computed and we have

$$\mathbf{R} = \begin{bmatrix} B_1 \\ B_2 \\ \vdots \\ B_s \end{bmatrix} = \begin{bmatrix} W_1 R_1 \\ W_2 R_2 \\ W_3 R_3 \\ W_4 R_4 \end{bmatrix} = \begin{bmatrix} 0.533 & 0.451 & 0.015 & 0 \\ 0.280 & 0.362 & 0.358 & 0 \\ 0.242 & 0.728 & 0.030 & 0 \\ 0.279 & 0.037 & 0 & 0.684 \end{bmatrix}. \tag{27}$$

According to the principle of the maximum membership, it can be seen from the matrix R that the level of geological influencing factors is excellent, the level of pile-influencing factors and cushion-influencing factors are good, and the level of construction-influencing factors is bad. The analysis conclusion is consistent with the reality that no preloading was performed to the target road section.

According to equation (25), the comprehensive evaluation vector for the postconstruction settlement of CFG pile composite subgrade can be obtained as

$$B = W \circ \mathbf{R} = \left[\, 0.222 \;\; 0.275 \;\; 0.262 \;\; 0.192 \,\right]. \tag{28}$$

According to the principle of maximum membership, the evaluation result of the postconstruction settlement is good. Namely, the range of the postconstruction settlement is [100 mm, 200 mm).

The construction of the target road section was completed and opened to traffic in July 2015. The observation frequency of the postconstruction settlement is shown in Table 10 and the collected postconstruction settlement data are shown in Figure 5.

According to the field observation data, the current settlement is 88.7 mm. Using the hyperbolic method, the final postconstruction settlement of the CFG pile composite subgrade after 15 years operation is 164.23 mm, which satisfies the calculation and evaluation results. Since the road section is a transitional section at the bridgehead, the allowable value of its postconstruction settlement should be less than 100 mm. Hence, certain remedial measures, such as

Table 8: Index value and normalized value of geological and pile secondary influencing factors.

Index	Geological influencing factors U_1			Pile influencing factors U_2			
	u_{11} (m)	u_{12} (MPa)	u_{13} (kPa)	u_{21} (MPa)	u_{22} (m)	u_{23} (m)	u_{24} (m)
Index value u_{ij}	22.6	6.45	9.5	8.0×10^3	25.0	0.4	2.2
Normalized value y_{ij}	0.405	0.198	0.124	0.599	0.078	0.472	0.310

Table 9: Index value and normalized value of cushion and construction secondary influencing factors.

Index	Cushion influencing factors U_3			Construction influencing factors U_4			
	u_{31} (m)	u_{32} (MPa)	u_{33} (°)	u_{41} (m)	u_{42} (mm/d)	u_{43} (m)	u_{44} (d)
Index value u_{ij}	0.3	100.0	35.0	5.3	80.0	0.0	0.0
Normalized value y_{ij}	0.346	0.433	0.231	0.101	0.232	1.000	1.000

Table 10: Monitoring frequency of postconstruction settlement.

Period	0~6 months	7~18 months	18~30 months
Frequency	2 times/month	1 time/month	1 time/2 months

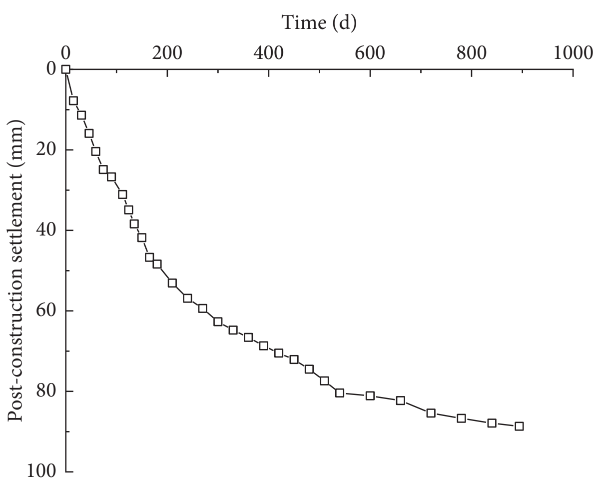

Figure 5: Postconstruction settlement monitoring data.

grouting, are necessary for this road section so as to meet the regulations.

7. Conclusion

In this paper, a two-level fuzzy comprehensive evaluation method is proposed for evaluating the postconstruction settlement of the CFG pile composite subgrade. Four primary influencing factors and 15 secondary factors are selected as the indexes to build the two-level evaluation system.

The entropy weight method and normal membership function with the normalization process are used to describe the fuzzy relationship between the evaluation results and the influencing factors.

A real bridgehead road section example in Guangdong Province has been selected to validate the proposed fuzzy comprehensive evaluation method. The evaluation results of the proposed method are in consistent with the field test results. Hence, the proposed fuzzy comprehensive evaluation method can be used to evaluate the construction quality of the CFG pile composite subgrade.

The FCE method requires a large amount of data and is complicated to calculate. Moreover, the samples used in this paper to calculate the weight of influencing factors are mainly from Guangdong Province, China, which has certain limitations. Moving forward, efforts will be made to explore how to reduce the subjectivity in the determination of evaluation factors and weights and therefore to construct a more rational and adaptive FCE method.

Data Availability

The data used to support the findings of this study are presented in the tables and figures.

Disclosure

This work is an original one conducted at Xuzhou University of Technology. The work described has not been submitted elsewhere for publication, in whole or in part.

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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