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Research Article

Weighted-Combined Model for Reclaimed Foundation Settlement Prediction in Coastal Sludge-Bearing Composite Stratum

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Foundation settlement prediction is significant to the reuse and management of the reclaimed land from the sea by dykes where composite stratum of many strata with different physical and mechanical properties is encountered. Toward the foundation settlement analysis of reclaimed land in the Yellow Sea composite stratum in eastern China, a weighted-combination model is proposed in this paper combining the hyperbolic model, exponential curve model, and Asaoka model. First, the weight coefficient of the weighted-combination model is calculated by the reciprocal square method of average absolute error (MAE). Second, the settlement prediction results of different models are evaluated by the absolute error, MAE, root-mean-square error, and mean absolute percentage error. Finally, the settlement mechanism of reclaimed foundations in a composite stratum is analyzed from the point of view of the multistratum coupling, and the adaptability of different models to the settlement prediction of reclaimed foundations in a composite stratum is discussed. The results show that the predicted settlement duration curves of the weighted-combined model are in good agreement with the measured settlement duration curves, and the prediction performance is better than that of the hyperbolic model, exponential curve model, and Asaoka model. The MAE of the weighted-combination model is 75.7% lower than that of the exponential curve model, 90.2% lower than that of the hyperbolic model, and 70% lower than that of the Asaoka model. This model provides a new way to predict the settlement of reclaimed foundations in a similar composite stratum.

1. Introduction

The area of urban land is decreasing day by day, and reclamation of land from the sea [1–3] is one of the effective ways to alleviate the shortage of land use. The engineering properties of reclaimed sludge are extremely poor [4, 5], so it is necessary to dry for a long time to form a surface hard shell layer before construction operation can be carried out. To speed up the construction progress, plain fill is often backfilled on the surface of the reclaimed foundation to improve the surface strength of the reclaimed foundation, and the reclaimed foundation gradually changes from single stratum to multistratum. Reclaimed foundation in composite stratum with thick sludge interlayer is becoming more and more common. The consolidation settlement of reclaimed foundation in a composite stratum is large, which is easy to cause damage to nearby structures, such as house cracking and uneven settlement of pavement. In addition, the settlement law of reclaimed foundations in a sludge-bearing composite stratum is a three-stage inverted "S" shape, so it is difficult to evaluate the settlement of this kind of foundation with high accuracy. Therefore, it is of great significance to accurately predict the settlement of reclaimed foundations in a composite stratum.

At present, settlement prediction is mainly divided into two categories, one is the settlement prediction of a single stratum foundation, and the other is the settlement prediction of the composite stratum foundation. In the settlement prediction of a single stratum foundation, the empirical equation method has simple calculation steps and is widely used in practice [6]. Some scholars have applied the Peck equation to the prediction of foundation settlement caused by rectangular pipe jacking in the sludge stratum [7]. A three-point hyperbolic combination model [8] is used to predict the settlement of construction waste subgrade. With the rapid development of coastal cities in China, infrastructure construction is carried out on a large scale on the reclaimed foundation. The Asaoka method [9–12], hyperbolic method [13], and exponential curve method have been widely used to predict the settlement of reclaimed foundation in the marine soft soil and achieved good results [14, 15].

Numerical simulation is also often used to predict the settlement of a single stratum foundation [16–18], for example, the finite-element method is used to predict the surface settlement of collapsible loess high-fill foundation, coral calcareous sand foundation, and shield tunnel under the influence of grouting layer [19–21]. However, the numerical simulation method cannot repeat modeling, and can only provide phased predicted values. In addition, numerical simulation is dependent on soil parameters, and the sampling disturbance of the sludge layer of reclaimed foundation in a composite stratum is large, so the parameters cannot be accurately measured by laboratory tests, which leads to a large deviation between simulated values and measured values.

Machine learning methods have been used [22, 23] to predict the settlement of cohesionless soils, such as artificial neural networks (ANN) [24–26], support vector machine (SVM) [27], evolutionary polynomial regression (EPR) [28], and so on. An optimized gray prediction model and a one-dimensional double-hidden-layer BP neural network [29] are used to predict the settlement of the sandy pebble foundation. These works focus on the settlement prediction of a single stratum, which lays a foundation for the settlement prediction of a composite stratum foundation. Due to the special needs of urban development, composite stratum foundation is becoming more and more common. Some scholars have made some beneficial explorations in the settlement prediction of composite stratum foundations. Zhang et al. [30] established a three-dimensional numerical model of the tunnel through the finite-element program Midas-GTS and analyzed the land subsidence law caused by shallow tunnel construction in the dry sand mixed stratum. Feng et al. [31] proposed an artificial bee colony-back-propagation model (ABC-BP model) to predict the deep horizontal displacement and surface subsidence of clay composite stratum. Lan and Wang [32] proposed a GSPM model based on the logistic and hyperbolic models for heightened and thickened soil–sand mixed dam. The above-mentioned works are mostly subjected to the settlement prediction methods of single stratum [12]. Very rare reports have done toward the foundation settlement prediction of the composite stratum which is mostly different clay composite stratum or clay and sand composite stratum.

The geological characteristics of reclaimed foundations in coastal composite stratum include plain fill layer, clay layer, and deep sludge interlayer. The material composition and physical as well as mechanical properties of different layers are quite different. The coupling influence between different layers is unclear. The settlement law of reclaimed foundations in this kind of composite stratum is different from that of a single-stratum foundation. The settlement curve of reclaimed foundation in a composite stratum is inverted "S" shape in three stages. Therefore, it is necessary to accurately predict the settlement of reclaimed foundations in a composite stratum.

In this paper, the reclaimed foundation incomposite stratum along the Yellow Sea in eastern China is taken as the research object, aiming at the difficult problem of settlement prediction, a weighted-combination model for settlement prediction of reclaimed foundation in a composite stratum with thick sludge interlayer is proposed by integrating hyperbolic model, exponential curve model, and the Asaoka model. The combined prediction model makes greater use of the prediction results of each model and has the advantage of reducing the interference of accidental factors on the prediction results. The results of the combined prediction model are accurate and stable and have been widely used and developed in the settlement prediction [33]. The settlement prediction performance is compared for the weighted-combination model, hyperbolic model, exponential curve model, and the Asaoka model for the reclaimed foundation in a composite stratum. From the point of view of the multistratum coupling, the settlement mechanism of reclaimed foundation in a composite stratum is analyzed, and the adaptability of each model to the settlement prediction of reclaimed foundation in a composite stratum is discussed.

2. Settlement Prediction Models

The weighted-combination model was derived from commonly used models such as the hyperbolic model, exponential curve model, and the Asaoka model.

2.1. Hyperbolic Settlement Prediction Model. In 1980, Kodandaramaswamy and Rao [34] proposed a settlement prediction method based on hyperbolic fitting. The hyperbolic settlement prediction model assumes that the soil settlement and time change according to the hyperbolic law, its equation is as follows:

$$s_t = s_0 + \frac{t - t_0}{a + b(t - t_0)}, \quad (1)$$

where s_t is the settlement corresponding to t at any time; s_0 is the settlement corresponding to the initial time t_0; a,b is the undetermined coefficient, which is obtained by fitting the measured data.

2.2. Exponential Settlement Prediction Model. In 1959, Guoxi and Xiling [35] applied the exponential curve prediction method to the analysis of manhole foundation settlement. The exponential curve settlement prediction model considers that soil settlement has an exponential curve relationship with time. The equation is as follows:

$$s_t = (s_\infty - s_d)(1 - \alpha e^{-\beta t}) + s_d, \quad (2)$$

where α and β are the undetermined coefficients related to the drainage conditions of the foundation and the properties of the foundation soil; β_0 and β_1 are constants.

The parameters of the exponential curve model can be obtained by taking three points (t_1, s_1), (t_2, s_2), (t_3, s_3) from the measured settlement curve and bringing them into Equation (2). The three points taken in this article are: (17, 180.2), (56, 716.7), and (95, 1,005.5), the time interval $\Delta t = 39$ days.

2.3. Asaoka Method. In the 1970s, Asaoka [36] proposed the Asaoka settlement prediction method based on Mikasa's one-dimensional volume strain settlement equation. The advantage is that a small amount of short-term measured data can be used to derive a more reliable final settlement. The form of the consolidation differential equation is as follows:

$$\frac{\partial \varepsilon_v}{\partial_t} = C_v \frac{\partial^2 \varepsilon_v}{\partial z^2}, \quad (3)$$

where ε is the vertical strain; t is time; C_v is the coefficient of consolidation; z is the depth below the top surface.

Equation (3) can be expanded in the form of a series, and expressed as a differential equation:

$$s + a_1 \frac{ds}{dt} + a_2 \frac{d^2 s}{dt^2} + \ldots a_n \frac{d^n s}{dt^2} = b, \quad (4)$$

where s is the total settlement; a_1, a_2, …, a_n, and b are constants.

In practical engineering applications, the calculation of the first-order equation is often simpler, and Equation (4) can be simplified and written as a first-order equation:

$$s + a_1 \frac{ds}{dt} = b. \quad (5)$$

Defining the settlement at t as s_t, the difference equation can be derived from Equation (5) as follows:

$$s_j = \beta_0 + \beta_1 s_{j-1}, \quad (6)$$

where β_0 and β_1 are the constants.

If $t = t_j$, when t_j approaches infinity, in Equation (6), s_j is equal to s_{j-1} and equal to s_∞, substituting into Equation (6), the final settlement is as follows:

$$s_\infty = \frac{\beta_0}{1 - \beta_1}. \quad (7)$$

The Equation (6) can be transformed into:

$$AX = B, \quad (8)$$

where $A = \begin{pmatrix} s_{17} & s_{20} & \cdots & s_{92} \\ 1 & 1 & 1 & 1 \end{pmatrix}^T$; $B = \begin{pmatrix} s_{20} & s_{23} & \ldots & s_{95} \end{pmatrix}^T$; $X = \begin{pmatrix} \beta_0 & \beta_1 \end{pmatrix}^T$.

According to the measured settlement data, the matrix can be calculated. Then, $AX = B$ can be solved by Matlab to get the values of β_0 and β_1. Substituting β_0 and β_1 into Equations (6) and (7), one can calculate the settlement s_t and the final settlement s_∞ at any time.

2.4. Weighted Combination Model. The combined prediction model has the advantage of reducing prediction errors and has been widely used and developed in the settlement prediction. The weight coefficient is the key to the combined prediction model [37]. The weighted combination prediction model is a settlement prediction model based on the above three methods to obtain weights based on the average absolute error (MAE) reciprocal square method. MAE is an indicator to measure the accuracy of settlement prediction. Generally, the larger the calculated value of MAE, the lower the prediction accuracy of the corresponding single settlement prediction model, and the degree of influence of the single settlement prediction model in the combined model. The lower the value, the smaller the corresponding weight coefficient, and vice versa, the larger the corresponding weight coefficient. Based on this, a weighted combination prediction model based on the weighting factor defined by the MAE square reciprocal method to obtain the weight of each single prediction model is proposed.

Define the measured value of the settlement of the soft-soil foundation at time t as x_t, $t = 1, 2, 3, \ldots, N$, if n types of single prediction models are used for prediction, then the prediction value of the i^{th} single prediction method at time t is x_{it}, $i = 1, 2, 3, \ldots, n$.

When the i^{th} single prediction method is used for prediction, the MAE of the prediction produced is as follows:

$$\text{MAE} = \frac{1}{N} \sum_1^N |x_t - x_{it}|. \quad (9)$$

To further expand the influence of the MAE on the weight determination process of the combined model and improve the prediction accuracy, if l_i is the weight operator of the i^{th} single prediction method, the calculation equation is as follows:

$$l_i = MAE^{-2}. \quad (10)$$

Assuming ω_i is the weighting coefficient of the first single prediction method in the weighted combination prediction model, the calculation equation is as follows:

$$\omega_i = \frac{l_i}{\sum_1^n l_i}, \quad (11)$$

where $\sum_1^n \omega_i = 1, \omega_i \geq 0$.

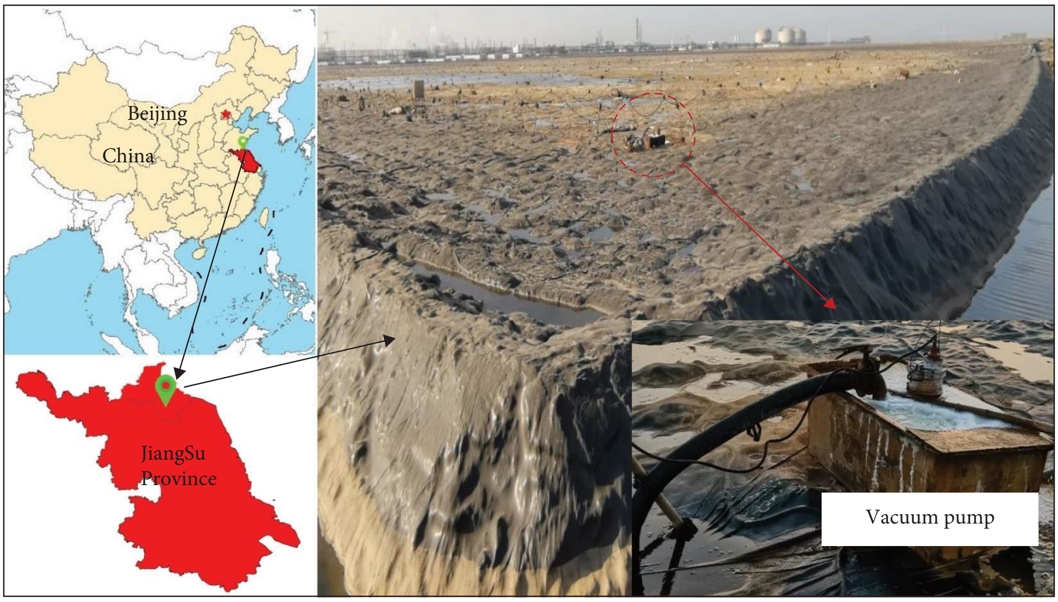

Figure 1: Location map of soft foundation project.

Then, the settlement prediction value of the weighted combination prediction model is as follows:

$$x_t = \sum_{1}^{n} x_{it}\omega_i. \tag{12}$$

3. Case Background and Settlement Characteristic

This paper studies the adaptability of the hyperbolic model, exponential curve model, Asaoka model, and weighted-combination model to the settlement prediction of reclaimed foundation in the composite stratum, taking the reclaimed foundation in the composite stratum along the Yellow Sea in eastern China as an example.

3.1. Project Overview and Engineering Geological Conditions. The reclaimed foundation in a composite stratum project is located in Lianyungang City, Jiangsu Province, China. Its geographical location and project site are shown in Figure 1. The length of the foundation is about 664 m, the width is about 504 m, and the treatment area is about 0.34 km^2. The vacuum preloading method is adopted for treatment, and the degree of consolidation of foundation should not be less than 80%.

The monitoring area of the reclaimed foundation is large, Therefore, the preloading area is divided into 12 monitoring areas, as shown in Figure 2(a). Taking the 1–4 areas of reclaimed foundation in a composite stratum as an example, the typical geological profile and the layout of settlement monitoring points are shown in Figures 2(b) and 3, respectively. The average settlement value of all monitoring points in each area is taken as the settlement value of this area, and the surface settlement is monitored by a high-precision Leica total station, as shown in Figure 2(c). The surface monitoring work of this project started on November 12, 2020, and ended on April 21, 2021, when the degree of foundation consolidation reaches 80% and the unloading requirements are met, the corresponding deformation monitoring will be stopped. The monitoring period amounted to 161 days.

The reclaimed foundation in a composite stratum consists of a plain fill layer, clay layer, sludge layer, silty clay layer, and silt layer from top to bottom in the survey depth range.

The average thickness of the first layer of plain fill is 1.65 m, with uneven and high compressibility, good air permeability, and poor engineering performance. The second layer of clay has uniform soil quality and a smooth section. The average thickness is 1.78 m, which has high compressibility and poor engineering performance. The average thickness of the third layer sludge is 14.23 m, the average water content can reach 61.1%, the air permeability is poor, the compressibility is high, and the engineering performance is extremely poor. The average thickness of silty clay in the fourth layer is 0.95 m, with medium compressibility and average engineering performance. The fifth layer of silt has an average thickness of 2.45 m, medium compressibility, and average engineering performance.

3.2. Settlement Characteristics of Reclaimed Foundation in a Composite Stratum. According to the average settlement data of 1–4 and 1–10 areas of reclaimed foundation with thick sludge interlayer composite stratum, the settlement characteristics of the reclaimed foundation are analyzed. The isochronous settlement curve of 161 days and $\Delta t = 3$ days in the two areas are shown in Figure 4, and the average settlement rate is shown in Figure 5.

It can be seen from Figure 4 that the settlement duration curve of reclaimed foundation in a composite stratum with thick sludge interlayer is approximately inverted "S" shape. The curve trend can be divided into three stages. In the first

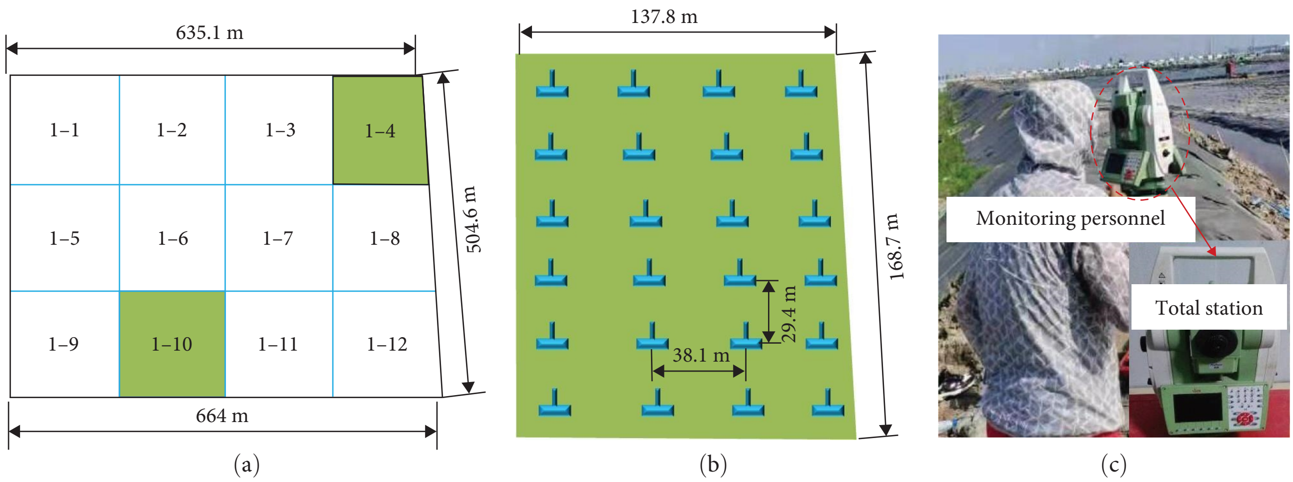

FIGURE 2: (a) Site monitoring zones, (b) layout of measuring points in Zones 1–4, and (c) site monitoring drawings.

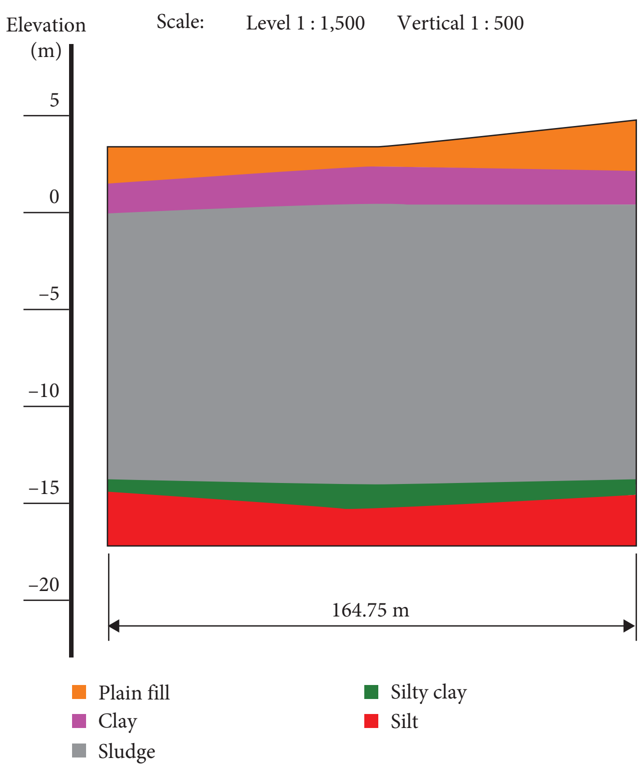

FIGURE 3: Typical geological profile of reclaimed foundation in Zones 1–4 of composite stratum.

stage, the settlement curve shows a short-term gentle growth in the initial stage of vacuum preloading, and the settlement rate curve increases to the highest point (developing settlement stage).

In the second stage, the settlement curve shows a rapid growth trend, and the settlement of the foundation mainly occurs in this stage. In this stage, the settlement in 1–4 area accounts for 69.7% of the total settlement, and that in 1–10 area accounts for 69.3% of the total settlement. The settlement rate curve fluctuates down from the highest point (rapid settlement stage). In the later stage of vacuum preloading, the settlement rate curve tends to be stable when it drops to 2 mm/day, and the settlement curve gradually converges (convergence settlement stage).

4. Settlement Prediction Result and Comparison

To compare and evaluate the prediction performance of the weighted-combination model, hyperbolic model, exponential curve model, and Asaoka model, the known settlement data which lasted 161 days were divided into two parts. The settlement data from the 2nd to the 95th day were used to fit the parameters of hyperbolic model, exponential curve model, and Asaoka model and determine the weight of the weighted-combined model. The settlement data from the 98th to the 161st day were used to test and evaluate the extrapolation prediction performance of each prediction model.

4.1. Prediction Results of Different Models. The parameters and weights of the hyperbolic model, exponential curve model, and Asaoka model are shown in Tables 1 and 2. The weight coefficient of the weighted-combination model is obtained by Equations (10) and (11).

The prediction of each model on the 98^{th}–161^{st} day of reclaimed foundation in Zones 1–4 and Zones 1–10 of composite stratum and the prediction of measured settlement duration curve are shown in Figures 6 and 7.

It can be seen from Figures 6 and 7 that the predicted settlement value of the hyperbolic model and Asaoka model is less than the measured value, the predicted settlement value of the exponential curve model is greater than the measured value, and the predicted settlement value of weighted-combination prediction model is in good agreement with the measured value.

The equation for calculating the absolute value of error is as follows:

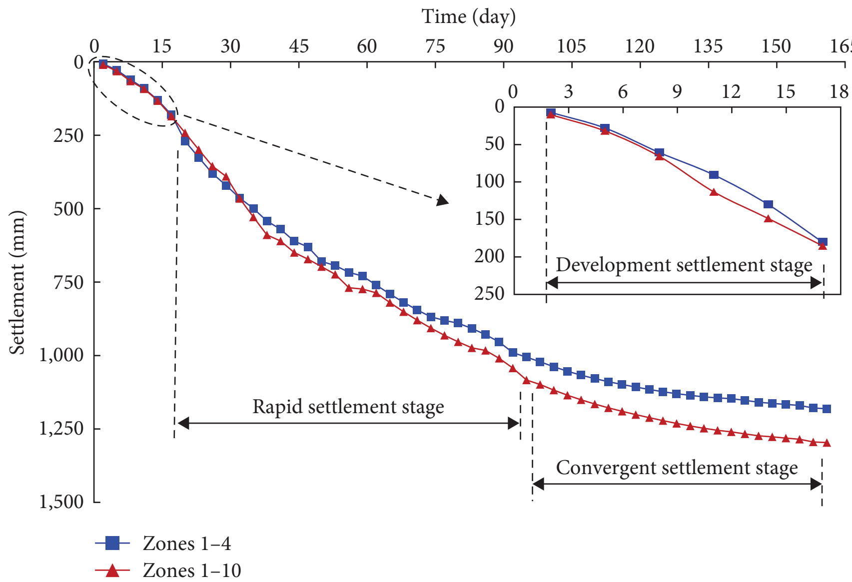

Figure 4: Average settlement duration curve of reclaimed foundation in a composite stratum.

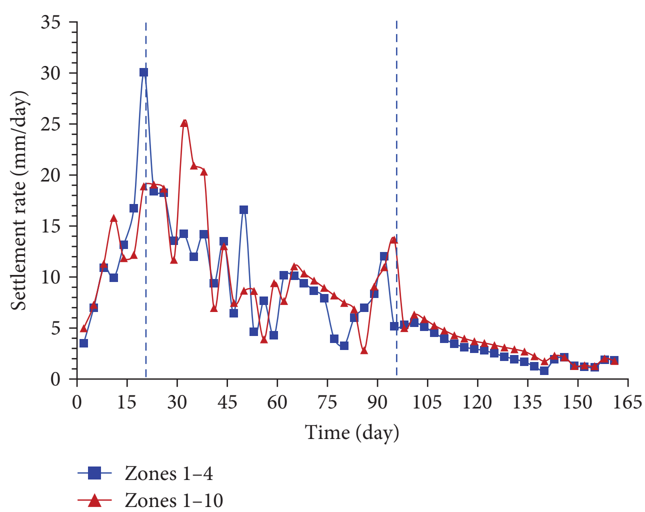

Figure 5: Duration curve of average settlement rate of reclaimed foundation in a composite stratum.

Table 1: Prediction models and weights in Areas 1–4.

Predictive model	Model equation	Weight coefficient
Hyperbolic model	$s_t = 180.2 + \frac{t-17}{0.0408+0.0008(t-17)}$	0.0598
Exponential curve model	$s_t = (1{,}342.22 + 378)(1-0.811392e^{-0.015880t})-378$	0.3738
Asaoka model	$s_t = 72.3373 + 0.9392 \times s_{t-1}$	0.5664

Table 2: Prediction models and weights in Areas 1–10.

Predictive model	Model equation	Weight coefficient
Hyperbolic model	$s_t = 185.2 + \frac{t-17}{0.0468+0.0006\,(t-17)}$	0.0708
Exponential curve model	$s_t = (1{,}449.74 + 424)(1-0.811392e^{-0.015890t})-424$	0.3990
Asaoka model	$s_t = 73.085 + 0.9458 \times s_{t-1}$	0.5302

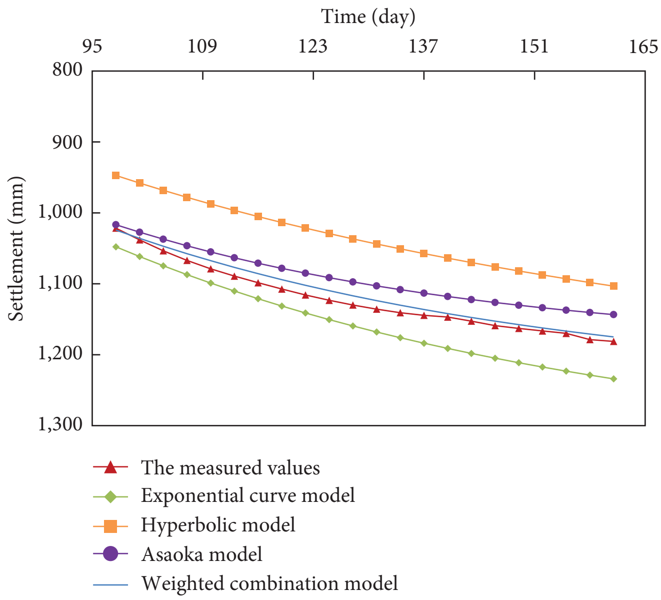

Figure 6: Predicted-settlement duration curves of various models in Areas 1–4.

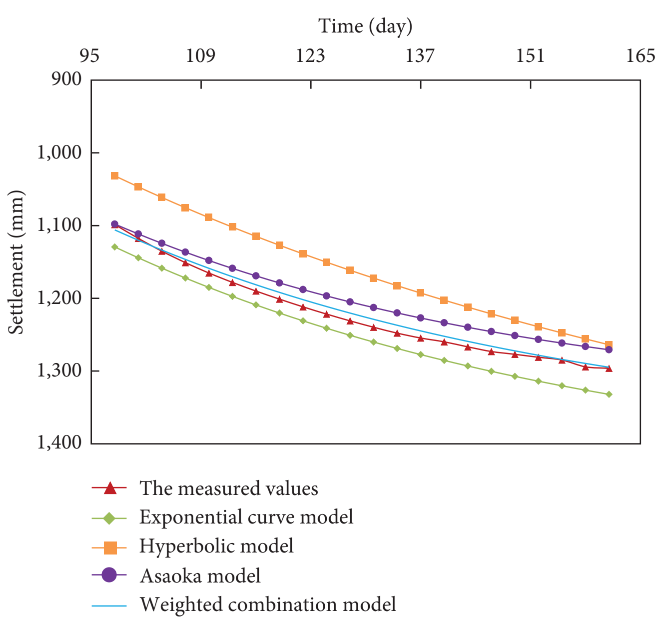

Figure 7: Predicted-settlement duration curves of various models in Areas 1–10.

$$\delta = |\hat{x}_t - x_t|, \tag{13}$$

where $\hat{x}_t$ is the predicted value; x_t is the measured value.

The time curves of absolute value of prediction error of each model for the reclaimed foundation in a composite stratum are shown in Figures 8 and 9. In Figure 8, according to the absolute duration curve of error in Zones 1–4, the fluctuation range of absolute value of error in hyperbolic model is 74.2–94.2 mm; the absolute value of the model error

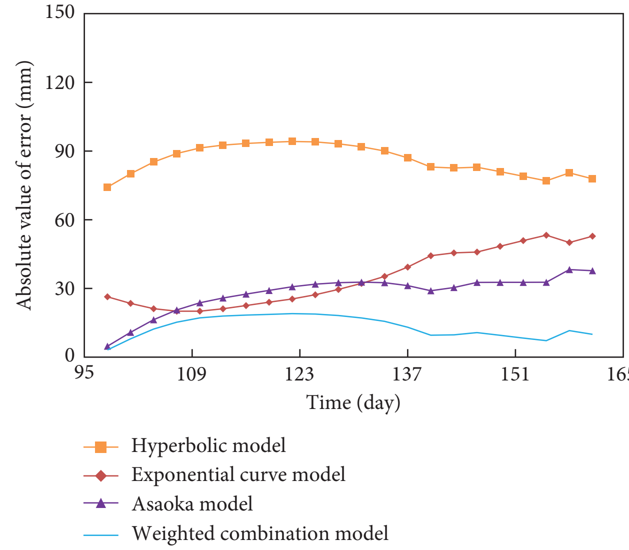

Figure 8: Duration curve of absolute error values of each model in Zones 1–4.

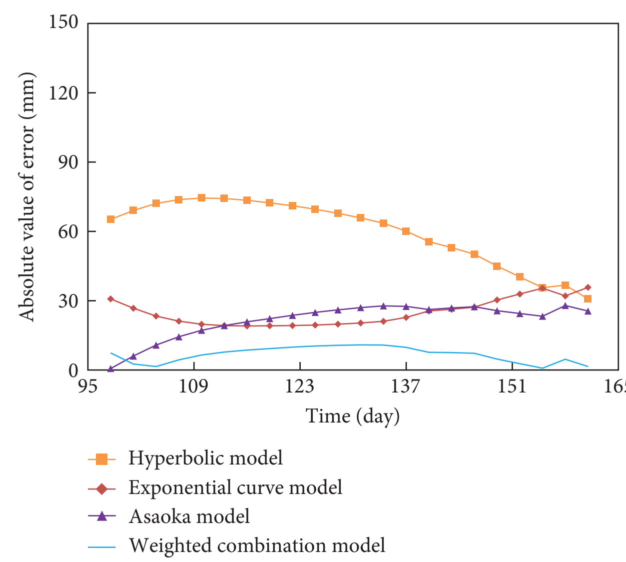

Figure 9: Duration curve of the absolute error value of each model in Zones 1–10.

of exponential curve value fluctuates from 20 to 53.3 mm; the range of absolute error of Asaoka model is 4.8–38.2 mm; the absolute value of the error of weighted-combined model fluctuates from 2.1 to 13.6 mm. In Figure 9, according to the duration curve of absolute error value in 1–10 region, the fluctuation range of absolute error value of the hyperbolic model is 32.4–76.2 mm; the absolute value of exponential curve model error fluctuates from 19.1 to 35.8 mm; the absolute value of Asaoka model error fluctuates from 0.6 to 27.9 mm; the absolute value of the error of weighted-combined model fluctuates from 0.8 to 10.9 mm. In Zones 1–4, the fluctuation range of absolute error of the weighted combined model is 57.5% of the hyperbolic model, 34.5% of exponential curve model, and 34.4% of the Asaoka model;

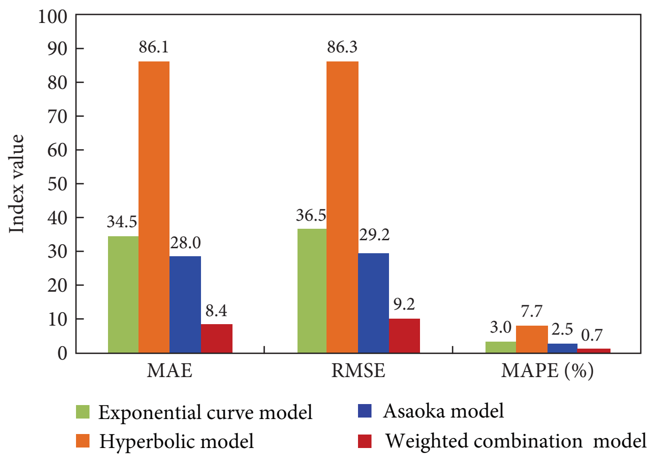

Figure 10: Comparison of prediction indexes of each model in Areas 1–4.

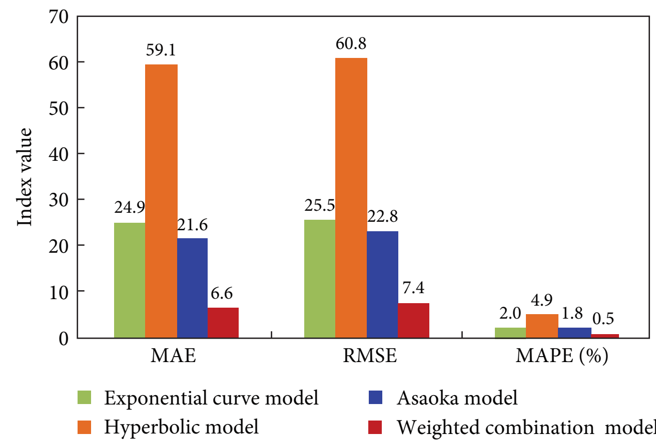

Figure 11: Comparison of prediction indexes of each model in Areas 1–10.

the range of absolute error of the weighted-combined model is 23.1% of the hyperbolic model, 60.5% of exponential curve model and 37% of Asaoka model.

4.2. Comparison of Prediction Performance. In order to compare the predictive performance of different models, the MAE in Equation (9), root-mean-square error (RMSE), and average absolute percentage error (MAPE) are used as evaluation indexes to analyze the prediction accuracy and stability of each model for reclaimed foundation settlement in a composite stratum. The equation of each evaluation index is as follows:

$$\mathrm{RMSE}=\sqrt{\frac{1}{N}\sum_{t=1}^{N}(\hat{x}_t-x_t)^2}, \tag{14}$$

$$\mathrm{MAPE}=\frac{100\%}{N}\sum_{t=1}^{N}\left|\frac{\hat{x}_t-x_t}{x_t}\right|, \tag{15}$$

where $\hat{x}_t$ is the predicted value; x_t is the measured value.

The prediction indexes of MAE, RMSE, and MAPE by weighted-combination model, hyperbolic model, exponential curve model, and Asaoka model for the reclaimed foundation in a composite stratum are shown in Figures 10 and 11.

It can be seen from Figures 10 and 11 that the MAE of the weighted-combined model in Zones 1–4 is 24.3% of that of the exponential curve model, 9.8% of the hyperbolic model, and 30% of that of the Asaoka model. RMSE is 25.2% of the exponential curve model, 10.7% of the hyperbolic model, and 31.6% of the Asaoka model; MAPE is 23.7% of the exponential curve model, 9.4% of the hyperbolic model, and 29% of the Asaoka model. The MAE of the weighted-combination model is 26.5% of that of the exponential curve model, 11.2% of that of the hyperbolic model, and 30.6% of that of the Asaoka model; RMSE is 29% of exponential curve model, 12.2% of hyperbolic model and 32.4% of Asaoka model; MAPE is 26.6% of the exponential curve model, 11% of the hyperbolic model and 30.9% of the Asaoka model.

The MAE and MAPE of the weighted-combination model are less than those of the exponential curve model, hyperbolic model, and Asaoka model. Therefore, the weighted-combination model is better than the exponential curve model, hyperbolic model, and Asaoka model in predicting the settlement of reclaimed foundation in a composite stratum. The RMSE and absolute error fluctuation range of the weighted-combination model are smaller than those of the exponential curve model, hyperbolic model, and Asaoka model. Therefore, the weighted-combination model is better than the exponential curve model, hyperbolic model, and Asaoka model in predicting the settlement of reclaimed foundation in a composite stratum.

5. Further Discussion of Predictive Performance on Different Settlement Stages

The predicted settlement duration curve of the weighted-combined model is in good agreement with the measured settlement duration curve, and its prediction accuracy and stability are better than those of the hyperbolic model, exponential curve model, and Asaoka model. The reasons for this are discussed in depth from the angle of multistratum coupling influence.

Under the vacuum preloading of reclaimed foundation in a composite stratum, the pore water in the soil is discharged along with the precast vertical drainage plate (PVD), the pore water pressure gradually dissipates, and the soil settles and consolidates. The stratum composition and physical and mechanical properties of the reclaimed foundation in a composite stratum have great spatial differences, and the settlement law of reclaimed foundation in a composite stratum is different from that of a single soil foundation due to the coupling influence of multiple strata. The settlement curve of this project is characterized by a three-stage inverted "S" shape, which is mainly divided into the settlement development stage, rapid settlement stage, and convergence settlement stage.

The first stage is the settlement development stage. Studies have shown that the initial settlement of the soil layer with better exhaust conditions after construction is even more

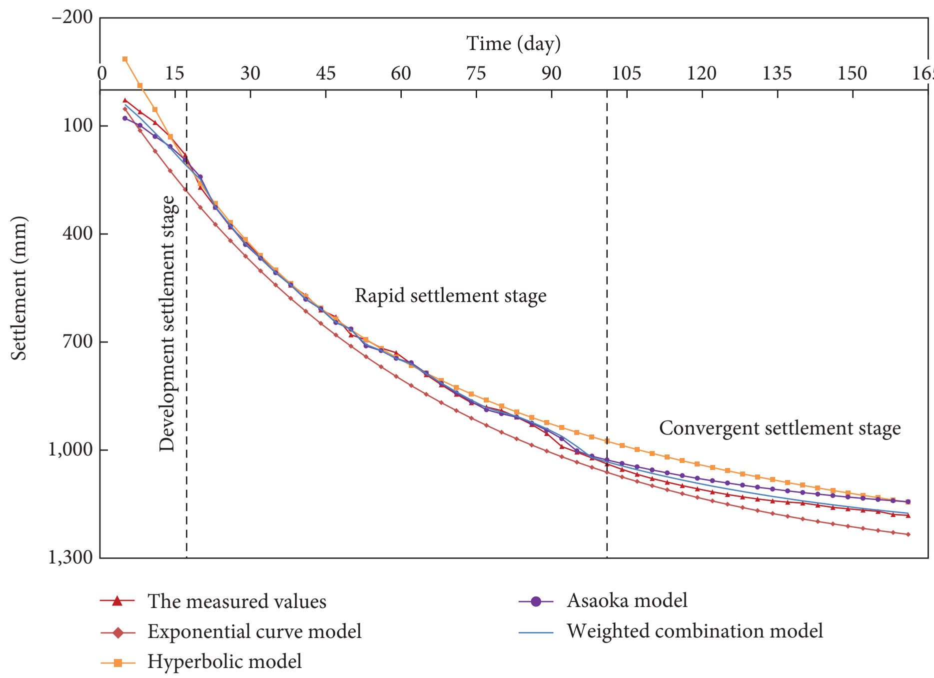

Figure 12: All-process prediction and measured settlement duration curves of each model in Areas 1–4.

than twice that of the soil layer with worse exhaust conditions [38]. The first layer of reclaimed foundation in a composite stratum is plain fill with an average thickness of 1.65 m, and the second layer is clay with an average thickness of 1.78 m, which has good exhaust conditions and is at the top layer, and the vacuum degree transmission speed is fast. The third layer is a deep sludge layer with an average thickness of 14.23 m, which has poor exhaust conditions and large thickness, and it takes a certain time for vacuum transfer. Therefore, the settlement in the development settlement stage mainly occurs in the upper soil layer.

The second stage is the rapid settlement stage. The vacuum degree is gradually transferred from the upper soil layer to the deep sludge layer, and a large amount of water in the sludge layer is discharged, which leads to the settlement and consolidation of the soil. Because of its high-water content [39, 40], high compressibility [41, 42], and much thicker than other soil layers, the sludge layer is a representative subsidence layer. At the same time, the coupling settlement effect exists in the upper soil layer, so the settlement curve shows a trend of rapid increase. Most of the settlement of the foundation occurs at this stage during vacuum preloading.

The third stage is the convergence stage. A large amount of pore water in the soil is discharged, the pore water pressure gradually decreases, the effective stress of the soil gradually increases, the soil is consolidated and dense, and the settlement rate slows down. At the same time, soil compaction, pore sealing in soil, poor air permeability, and blockage of drainage plate [43–45] all lead to a serious reduction of vacuum degree transfer efficiency in the later stage of vacuum preloading, further slowing down the settlement rate. The settlement curve shows a convergence trend.

To explore the adaptability of each prediction model to different settlement stages, taking Areas 1–4 as an example, the whole process prediction settlement duration curve of each model is compared with the measured settlement duration curve, as shown in Figure 12.

The predicted settlement duration curve of the weighted-combined model is in good agreement with the measured settlement duration curve, and the prediction accuracy is better than that of the hyperbolic model, the exponential curve model, and the Asaoka model. Under the influence of multistratum coupling, the settlement law of reclaimed foundations in a composite stratum is significantly different from that of a single soil foundation. The hyperbolic model, exponential curve model, and Asaoka model show limitations in predicting the settlement of reclaimed foundations in a composite stratum. The predicted settlement duration curve of the hyperbolic model is in good agreement with the measured settlement duration curve in the transitional stage between the developing settlement stage and rapid settlement stage, but it shows a trend of premature convergence in the late stage of the rapid settlement stage and convergence settlement stage.

The predicted settlement duration curve of the exponential curve model diverges seriously in the convergence settlement stage. The predicted settlement duration curve of the Asaoka model is in good agreement with the measured settlement duration curve in the rapid settlement stage, but it shows a trend of premature convergence in the convergence settlement stage. The weighted-combination model is in good agreement with the measured values in the three stages of settlement of reclaimed foundation in a composite stratum, especially in the convergence settlement stage, and has obvious advantages. The weighted-combination model can be combined with the hyperbola model, exponential curve model, and Asaoka model to adapt to different strata, so it has better adaptability to the prediction of ground settlement in composite strata under the influence of multistrata coupling.

The weighted-combination model has good stability in predicting the settlement of reclaimed foundations in a composite stratum. Compared with the hyperbolic model, exponential model, and Asaoka model, the fluctuation range of the absolute value duration curve of the prediction error of the weighted-combination model is smaller. The three-stage inverted "S"-shaped measured settlement duration curve contains various information characteristics under the influence of multistratum coupling, hyperbolic model, exponential curve model, and Asaoka model can only reflect the single information of the influence of a certain stratum, and different strata have different contributions to the different stages of settlement curve. The lack of information on the hyperbolic model, exponential curve model, and Asaoka model for a certain settlement stage is manifested in the wide fluctuation range of prediction error for later settlement. The weighted-combined model can fully reflect the information of different settlement stages, so the error fluctuation range of later settlement prediction is small.

6. Conclusions

Aiming at the difficult problem of settlement prediction of reclaimed foundation in a composite stratum, this paper proposes a weighted-combination model by integrating the hyperbolic model, exponential curve model, and Asaoka model, and compares and discusses the prediction performance of the weighted-combination model, hyperbolic model, exponential curve model and Asaoka model for settlement prediction of reclaimed foundation in a composite stratum. The main conclusions are as follows:

(1) The predicted-settlement duration curve of the weighted-combined model is in good agreement with the measured settlement duration curve of reclaimed foundation in a composite stratum, and the fluctuation range of absolute error value in 1–4 areas is between 2.1 and 13.6 mm, and that in 1–10 areas is between 0.8 and 10.9 mm.

(2) The weighted-combination model is superior to the hyperbolic model, exponential curve model, and Asaoka model in the prediction accuracy of the settlement of reclaimed foundation in a composite stratum. The weighted-combination model can combine the adaptability of each single empirical equation model to different strata, so it has good adaptability to the settlement prediction of reclaimed foundations in composite strata under the coupling influence of multiple strata. The MAE of the weighted-combination model in the areas 1–4 is 75.7% lower than that of the exponential curve model, 90.2% lower than that of the hyperbolic model, and 70% lower than that of the Asaoka model.

(3) Weighted-combination model is better than the hyperbolic model, exponential curve model, and Asaoka model in the prediction stability of the settlement of reclaimed foundation in a composite stratum. The weighted-combination model can fully reflect the information of each settlement stage of the reclaimed foundation under the influence of multistratum coupling. The RMSE of the weighted-combination model in the 1–4 areas is 74.8% lower than that of the exponential curve model, 89.3% lower than that of the hyperbolic model, and 68.4% lower than that of the Asaoka model.

Nevertheless, the proposed model has a good prediction effect on the reclaimed foundation in a composite stratum with a thick sludge interlayer. Its adaptability to the settlement prediction of reclaimed foundations in other composite strata needs to be verified by the engineering practice.

Data Availability

Any data and code used in this study can be available by requesting the corresponding author by email.

Ethical Approval

The authors confirm ethics approval was received for this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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