Hindawi
Advances in Civil Engineering
Volume 2019, Article ID 9453620, 11 pages
https://doi.org/10.1155/2019/9453620

Research Article

Differential Settlement of Intersecting Buildings in an Offshore Reclamation Project

Jing-Bo Su ,[1] Zheng-yang Yu,[1] Ya-Ru Lv ,[2] Yi-Huan Zhu,[3] and Hua-Qing Wang[4]

[1]*College of Harbour, Coastal and Offshore Engineering, Hohai University, Nanjing, Jiangsu, China*
[2]*The College of Mechanics and Materials, Hohai University, Nanjing, Jiangsu, China*
[3]*China Design Group Co. Ltd., Nanjing, Jiangsu, China*
[4]*Zhejiang University, Hangzhou, Zhejiang, China*

Correspondence should be addressed to Ya-Ru Lv; yaru419828@163.com

Received 8 October 2018; Revised 29 December 2018; Accepted 15 January 2019; Published 20 March 2019

Academic Editor: Khalid Abdel-Rahman

This paper addresses the problem of open gaps caused by differential settlement in the process of constructing sluice buildings in soft soil beach areas, combined with the construction of sluice and supporting facilities in a reclamation project. First, the change rules for the shear strength and compression modulus of soft soil under different consolidation degrees are studied by theoretical analysis. Then, an interaction model for soft soil and pile soil is established using the geotechnical finite element analysis software MIDAS/GTS NX. The change rules for the vertical and horizontal ultimate bearing capacities of a single pile with the degree of soil consolidation are studied. On this basis, a three-dimensional numerical analysis model of drainage sluice, seawall, cofferdam, and foundation soil is established, and the relationship between the degree of soil consolidation and the development of structural gaps caused by differential settlement is obtained. The research results show that the bearing capacity of a single pile increases greatly with the consolidation of soil around the pile and that the gap width between the structures in the project decreases with increasing consolidation. This paper provides a theoretical basis for the prediction of pile bearing capacity in the preliminary design stage and the evaluation and calculation of differential settlement of intersecting buildings in soft soil beach areas.

1. Introduction

Coastal reclamation has become an effective way to expand urban residential and construction land because of the rapid economic development, population growth, and population density in coastal areas. However, the coastal geological conditions are mainly thick silty soft soil, and there are many foundation reinforcement problems in reclamation projects. In addition, there are many reinforcement methods for soft soil foundations. The vacuum-surcharge preloading method combined with the cast-in-place pile reinforcement method has been widely considered because of the large increase in foundation bearing capacity and the small settlement after construction [1]. Therefore, the influence of vacuum-surcharge preloading on the physical and mechanical indexes of foundation soil, the mechanical characteristics of the cast-in-place pile, and the settlement reserve control method of intersecting buildings in soft soil beach area are discussed. Liu et al. [2] proposed a simple formula for predicting the shear strength of soils under arbitrary consolidation. Through triaxial and centrifugal model tests, the relationship between the degree of consolidation and shear strength index (c, φ) was studied by Bao and Zhou [3], and the results showed that this relationship is not linear but closer to hyperbolic. On the basis of a large number of consolidation and direct shear tests, the fitting formula between the consolidation degree and the shear strength index was given by He et al. [4]. Mu and Li [5] carried out consolidation experiments under different pressure conditions and obtained the dynamic evolution law for the compressive modulus under different consolidation conditions. Based on the existing code for building foundation treatment, two parameters were introduced, and the development law of shear strength and compressive modulus of underconsolidated soft soil with overlying load was proposed by Guan et al. [6]. Chen et al. [7] provided a numerical solution for the development of negative skin friction of a pile in nonlinear consolidated soil under different loads on a pile top. Applying the finite element software MIDAS/GTS to the inclined pile, a load was applied to determine the horizontal critical load and ultimate load of a single pile, and the horizontal bearing capacity of a single pile was obtained by Chatterjee and Choudhury [8].

With respect to controlling differential settlement, Zhou [9] chose to carry out the construction of a building after the settlement was stable in a sluice project with a soft soil foundation. Liu et al. [10] provided the design and construction basis for engineers by predicting the final consolidation settlement and settlement rate of the Yellow River underwater delta. Wang et al. [11] took a consolidation degree not less than 85% calculated from the measured settlement curve and a measured settlement rate not more than 2 mm/d for 10 consecutive days as the standards to determine construction time. However, there are few studies on the change rules in the bearing capacity of a single pile and the differential settlement of the superstructure with the degree of consolidation.

In this paper, the shear strength index and compressive modulus of clay at different consolidation stages under vacuum-surcharge preloading are studied by theoretical analysis. A pile-soil interaction model is established by MIDAS/GTS NX, and the variation law for the bearing capacity of a single pile with consolidation degree is obtained. Then, the development of different gap widths in the process of consolidation degree change is studied according to a three-dimensional numerical analysis model of drainage gate, seawall, cofferdam, and foundation soil. This paper provides a theoretical basis for the prediction of pile bearing capacity in the preliminary design stage and the evaluation and calculation of differential settlement of intersecting buildings in soft soil beach areas.

2. Project Overview

The paper is grounded in a drainage sluice project on soft foundation with 7 holes, a spacing of 6 m, a total net width of 42 m, and a gate bottom elevation of −2.0 m. It is located in the coastal beach area. According to the preliminary geological survey report, the landform in this area is a typical coastal plain landform and there is a deep muddy soil layer at the construction site. Therefore, vacuum preloading combined with the surcharge foundation treatment method is adopted, and the sluice foundation implements a cast-in-place pile foundation. Vacuum preloading is adopted first, vacuum preloading combined with surcharge preloading is implemented at later stages, and a plastic drainage plate (depth 15–27 m) is inserted to accelerate soil consolidation. The vacuum preloading construction schedules are as follows: (1) uniform vacuum treatment until the pressure reaches 65 kPa within 60 days; (2) intermittent for 20 days; (3) loading uniformly the first layer of filling soil until the pressure reaches 10 kPa within 10 days; (4) intermittent for 10 days; (5) loading uniformly the second layer of filling soil until the pressure reaches 30 kPa within 15 days; (6) intermittent for 10 days; (7) loading uniformly the third and fourth layers of filling soil until the pressure reaches 50 kPa within 10 days; and (8) intermittent for 20 days. The specific loading arrangement is shown in Figure 1.

The diameter of the cast-in-place pile is 1 m, the pile length is 32 m, and the concrete strength grade is C30. According to the geological survey report, the stratification and physical and mechanical parameters of the soil are shown in Table 1.

3. Change Rules for Mechanical Properties of Soil during Consolidation

The changes in the physical and mechanical properties of the soil during consolidation directly affect the change in the bearing capacity of the pile at different consolidation stages. Therefore, it is necessary to study the changes in soil physical and mechanical properties at different consolidation stages. Taking the effective internal friction angle and cohesion, the pore water pressure coefficient at shear failure, and the internal friction angle and cohesion obtained from consolidated undrained shear as the initial parameters and taking the total stress and effective stress parameters into account, the shear strength index varies in different consolidation stages as follows [12]:

$$\varphi_i = 2\ \arctan\sqrt{K'\left(U_i-1\right)+K_{\mathrm{cu}}}-90^{\circ}, \tag{1}$$

$$\begin{aligned} c_i &= \frac{K'\left(1-U_i\right)\sigma_{\mathrm{c}}+\sqrt{K_{\mathrm{cu}}}2c_{\mathrm{cu}}}{2\sqrt{K'\left(U_i-1\right)+K_{\mathrm{cu}}}} \\ &= \frac{1}{2}\left[\frac{K_{\mathrm{cu}}\sigma_{\mathrm{c}}+\sqrt{K_{\mathrm{cu}}}\,2c_{\mathrm{cu}}}{2\sqrt{K'\left(U_i-1\right)+K_{\mathrm{cu}}}}-\sqrt{K'\left(U_i-1\right)\sigma_{\mathrm{c}}}\right], \end{aligned} \tag{2}$$

where

$$\begin{aligned} K' &= \frac{1-\sin\varphi'}{1-\left(1-2A_{\mathrm{f}}\right)\sin\varphi'}\left[\tan^2\left(45^{\circ}+\frac{\varphi'}{2}\right)-1\right], \\ K_{\mathrm{cu}} &= \tan^2\left(45^{\circ}+\frac{\varphi_{\mathrm{cu}}}{2}\right). \end{aligned} \tag{3}$$

The constants K_{cu} and K' are variables related to the effective stress index and the total stress index and independent of the consolidation coefficient, and both are greater than 0 [13]; A_{f} is the pore water pressure coefficient at shear failure:

$$A_{\mathrm{f}} = \frac{u_{\mathrm{f}}\sigma_3}{u_0\left(\sigma_1-\sigma_3\right)}. \tag{4}$$

The initial consolidation pressure σ_{c} of each soil layer can be calculated from the depth of the corresponding soil layer in the geological survey report. According to the relevant indicators of the initial triaxial compression and direct shear test of the soil layer (Table 2), the relationship (Figures 2 and 3) between the shear strength index and soil consolidation degree of each consolidated soil layer can be obtained by equations (1) and (2). In the table, $c\prime$ and $\varphi\prime$ are

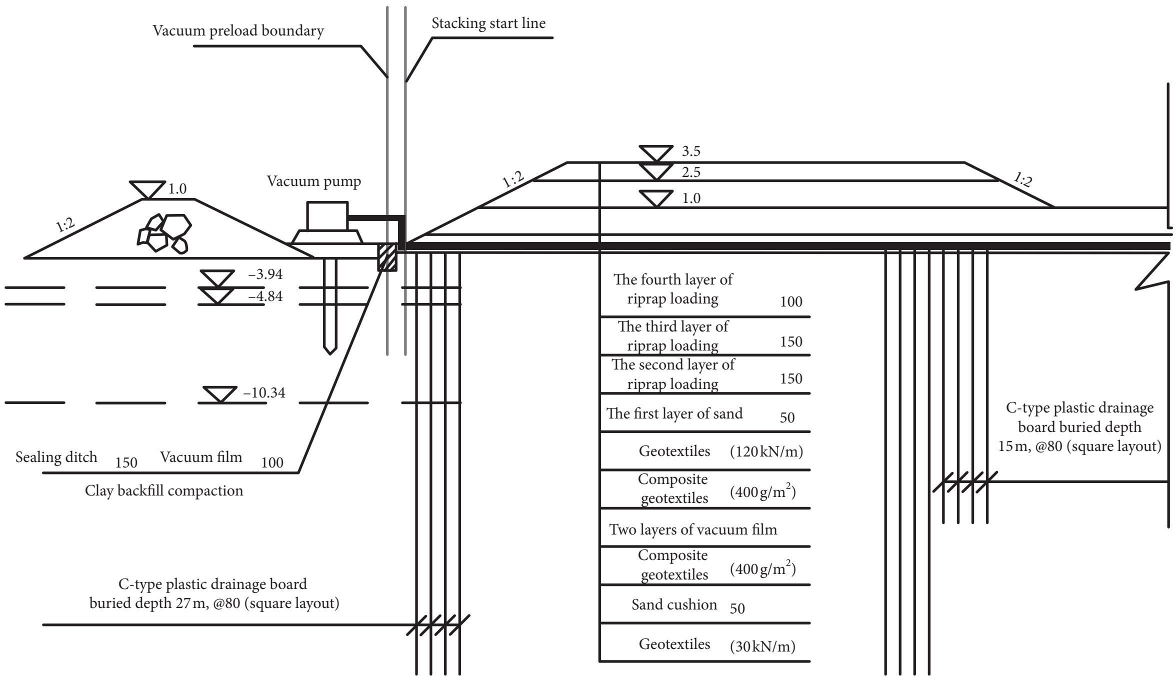

Figure 1: Application of vacuum preloading surcharge.

Table 1: Stratification and physical and mechanical parameters of soil.

Soil name	Thickness (m)	Bulk density (kN/m^3)	Compression modulus (MPa)	Poisson's ratio	Permeability coefficient (cm/s)	c' (kPa)	φ' (°)	c_{cu} (kPa)	φ_{cu} (°)
Sludge	1.44	15.9	2.01	0.35	3.67×10^{-6}	5	22.5	6	20.5
Sludge with sand	5.5	16.9	2.14	0.35	3.62×10^{-5}	8	29	9.46	28.4
Muddy clay	23	16.3	1.85	0.38	2.82×10^{-6}	6	29.6	7.96	29.1
Silt	3.4	21	15	0.3	8.2×10^{-4}	19.4	32.5	19.6	33
Clay	10	18.3	3.99	0.3	1.40×10^{-6}	18	31.3	18.65	32.5

Table 2: Initial consolidation pressure and initial shear strength index of the soil layers.

Consolidated soil layer	c' (kPa)	φ' (°)	A_f	c_{cu} (kPa)	φ_{cu} (°)	σ_c (kPa)
Sludge	5.0	22.5	1.0	6.0	20.5	29.45
Sludge with sand	8.0	29	0.27	9.46	28.4	104.11
Muddy clay	6.0	29.6	0.25	7.96	29.1	290.44

the shear strength parameters of soil in the initial state, where c' represents cohesion and $\varphi\prime$ represents internal friction angle. They are derived from the geological test report completed in the earlier stage of this study, in which we measured the shear strength parameters of different soil layers. Figures 2 and 3 show that the changes in the shear strength of different consolidation soil layers from the natural state (consolidation degree 0%) to complete consolidation (consolidation degree 100%) are different: the internal friction angle of the sludge increases by 40.47%, while the cohesion of the sludge decreases by 17.40%; the internal friction angle of the sludge with sand increases by 54.21%, while the cohesion of the sludge with sand decreases by 28.32%; and the internal friction angle of the muddy clay

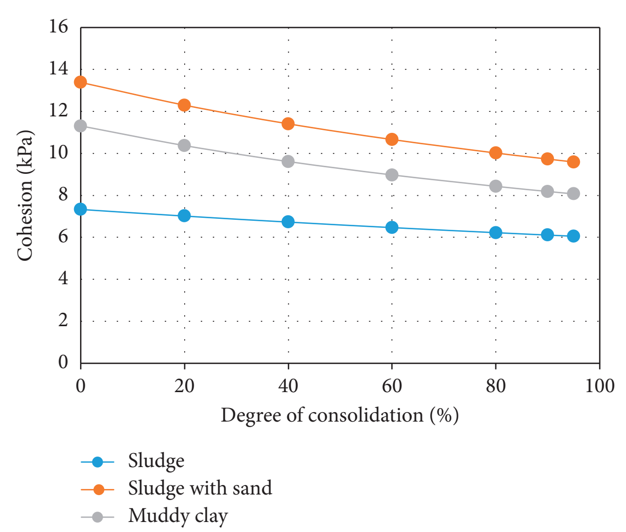

Figure 2: Relationship curve of cohesion and degree of consolidation.

increases by 54.35%, while the cohesion force of the muddy clay decreases by 28.63%. Generally, as the degree of consolidation increases, the internal friction angle in each

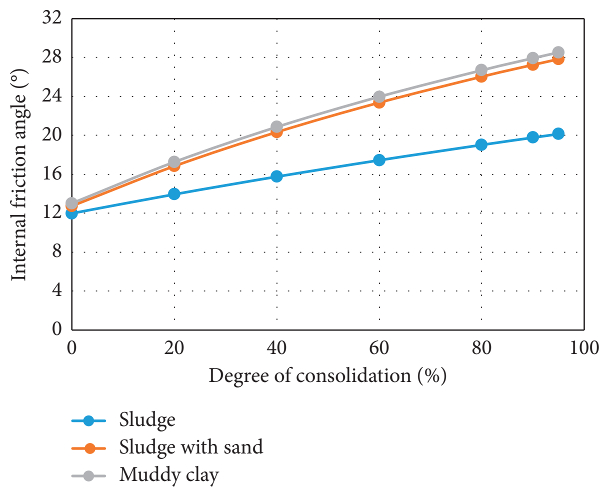

FIGURE 3: Relationship curve of internal friction angle and degree of consolidation.

consolidated soil layer increases, the cohesion decreases, and the variation ranges of sludge with sand and muddy clay are larger than that of sludge.

There is a correlation between the compressive modulus and the elastic modulus. Accurate analysis of the change in compressive modulus with different consolidation degrees is the premise of a reasonable value for the elastic modulus. The formula for calculating the modulus of compression proposed [14, 15] is as follows:

$$E_{t_0} = \frac{\Delta PH}{S_\infty - S_{t_0}} \left[1 - \frac{8}{\pi^2} \cdot e^{\left(\left(-\pi^2 C_v\right)/\left(4H^2\right)\right)\left(t_\infty - t_0\right)} \right], \quad (5)$$

where E_{t_0} is the compression modulus corresponding to consolidation time t_0; ΔP is the stress increment; S_∞ is the final settlement of saturated soil; S_{t_0} is the settlement of consolidation time t_0; t_∞ is the time required to complete the consolidation for the soil mass and generally takes the value corresponding to a consolidation degree equal to 95–99%; e is the void ratio; and H is the drainage distance. According to the definition of consolidation degree, the degree of consolidation U_{t_0} of saturated soft soil at a certain moment t_0 can be calculated as follows:

$$U_{t_0} = \frac{S_{t_0}}{S_\infty}. \quad (6)$$

The final settlement of saturated soft soil can be calculated as follows [16]:

$$S_\infty = \frac{\Delta PH}{E_S}. \quad (7)$$

Substituting equations (6) and (7) into equation (5), we can obtain

$$E_{t_0} = \frac{E_S}{1 - U_{t_0}} \left[1 - \frac{8}{\pi^2} \cdot e^{\left(\left(-\pi^2 C_v\right)/\left(4H^2\right)\right)\left(t_\infty - t_0\right)} \right]. \quad (8)$$

Equation (8) can be used as a mathematical expression reflecting the macroscopic variation law between the compressive modulus and the degree of consolidation of saturated soft soil. A finite element consolidation analysis model (Figure 4) based on MIDAS/GTS is established to study the consolidation process of vacuum-surcharge preloading and the corresponding ground deformation process in the engineering area and to provide the corresponding analysis data for the calculation of soil parameters during the consolidation process. The model area is 4 m × 4 m, and the depth is 55 m. The model is divided into 4464 hexahedral elements with a total of 5408 nodes. The Mohr–Coulomb yield criterion is adopted in the model, and a 0.8 m × 0.8 m drainage plate is considered. The simulation analysis process is based on the actual loading sequence, and the model analysis time is set to two years after construction.

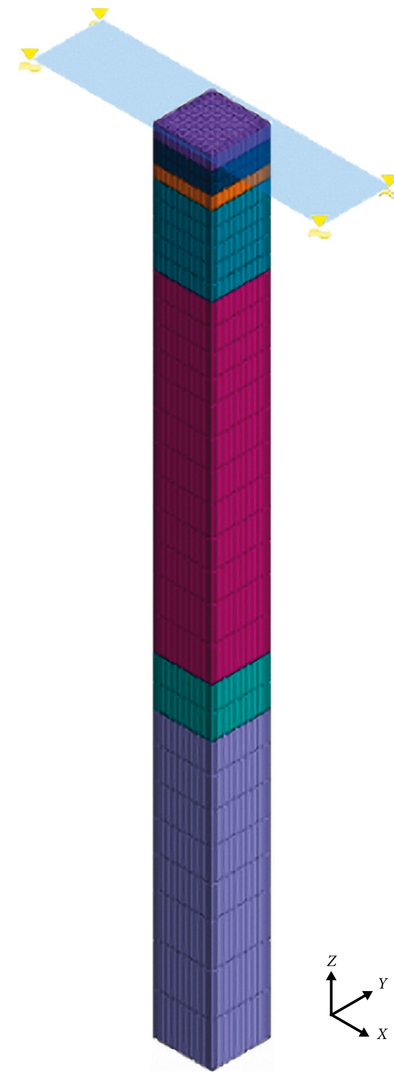

FIGURE 4: Consolidation analysis model.

The variation process of ground settlement with consolidation time during vacuum preloading to stable deformation is shown in Figure 5. Figure 5 illustrates that the curve reflects the loading process very well. The ground settlement is 1.49 m at the end of the vacuum-surcharge preloading construction (approximately 155 days). The final ground settlement is 1.92 m when the deformation is stable, so the degree of consolidation at the end of the vacuum-surcharge preloading construction is 77.6%, which is consistent with the actual design standard.

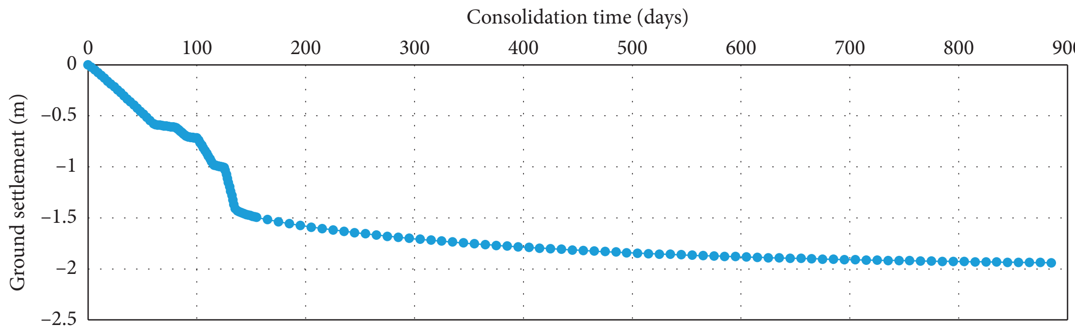

Figure 5: Ground settlement process from vacuum-surcharge preloading to stable settlement.

From the initial compressive modulus and permeability parameters (see Table 3, equation (8), and Figure 5), the relationship between the compressive modulus and the consolidation degree of each consolidated layer can be obtained (Figure 6). Figure 6 shows that the compressive modulus of each consolidated soil layer increases as the degree of consolidation increases; when the degree of consolidation is less than 60%, the growth is slow. However, when the degree of consolidation is greater than 60%, the growth rate is 8-9 times the growth rate of the previous period. The compressive moduli of sludge and sludge with sand increase slightly faster than that of muddy clay. References [5] and [6] record the actual variation of shear strength and compressive modulus obtained from their experiments on several soils, which is basically consistent with the variation obtained from our methods.

Table 3: Initial compression modulus and permeability parameters of the soil layers.

Consolidated soil layer	E_S (MPa)	k_v (cm/s)	C_v (m^2/s)
Sludge	2.01	$3.67 * 10^{-6}$	$7.53 * 10^{-8}$
Sludge with sand	2.14	$3.62 * 10^{-5}$	$7.91 * 10^{-7}$
Muddy clay	1.85	$2.82 * 10^{-6}$	$5.32 * 10^{-8}$

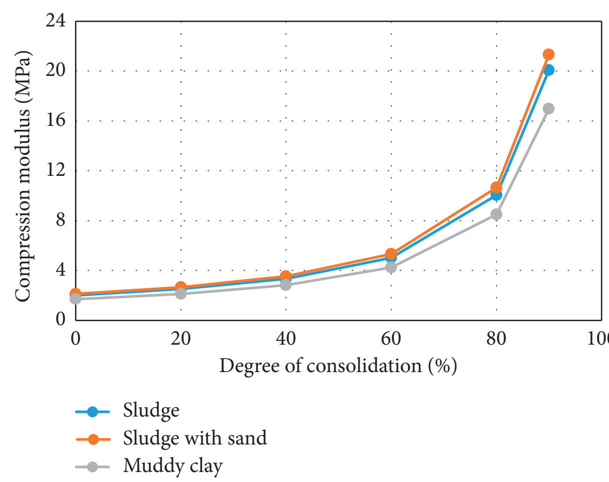

Figure 6: Change curve for the compressive modulus with degree of consolidation.

4. Study on Bearing Capacity of a Single Pile with Consolidation Degree

4.1. Finite Element Model of Pile-Soil Interaction. To study the change of bearing capacity of single piles at different consolidation stages, a pile-soil interaction model is established using the MIDAS/GTS NX software. The calculation range of the soil mass is 20 m × 20 m × 64 m. Three-dimensional hexahedral solid elements with 13000 units and 14331 nodes are used, and the Mohr–Coulomb model is used for soil material. The length of the pile is 32 m, and the diameter of the pile is 1 m. Beam elements with 33 units and 34 nodes are used for the pile. Contact elements are set between the pile and each layer of soil, and a pile tip element is set at the end of the pile. The finite element model is shown in Figure 7. In the analysis process, the initial stress field of the soil is considered, and the force-grading loading method is adopted.

On the basis of the compressive modulus of each soil layer in different consolidation stages, the elastic modulus is taken as 10–30 times the compressive modulus and the soft soil is taken as a smaller value; the ultimate shear strength (it is the control index chosen to limit the maximum frictional strength of each soil layer when MIDAS/GTS NX is used in our research.) in the pile-soil contact parameters is taken as the standard value of the ultimate lateral resistance × the perimeter of the pile. The shear stiffness modulus is taken as 5 times the elastic modulus; the normal stiffness modulus is taken as 10 times the shear stiffness modulus; and the bearing capacity of the pile end is taken as the standard value of the ultimate end resistance × pile cross-sectional area. The stiffness of the pile tip spring is related to the m value of the horizontal resistance coefficient of the foundation soil, and it is taken as the m value of the soil at the pile tip × the length of the pile × the cross-sectional area of the pile end; here, the m value of the silt at the pile tip is 8 MN/m^4. The ultimate lateral and vertical resistance of the pile and the m value are selected and used in accordance with the Technical Code for Building Pile Foundation (JGJ 94–2008) in the Industry Standards of the People's Republic of China. When the degree of consolidation is 80%, the parameters of pile-soil contact are shown in Table 4. Figures 8 and 9 show the comparison of load displacement curves obtained from measured and calculated vertical and horizontal test piles when the degree of consolidation is 80%. Figures 8 and 9 show that the pile-soil interaction model and parameters are suitable for the simulation of piles.

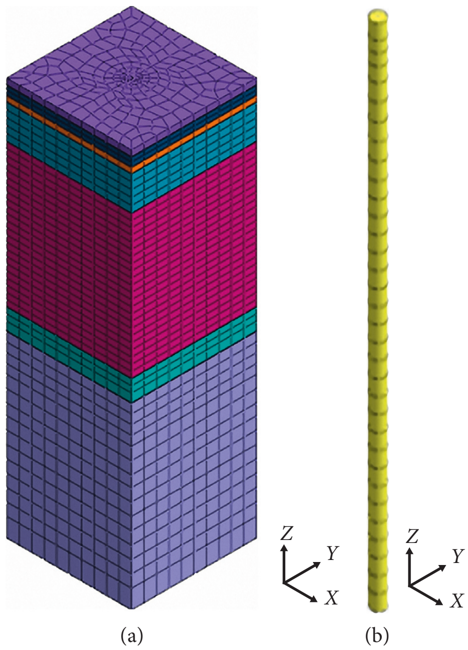

Figure 7: Finite element model of pile-soil interaction: (a) overall model; (b) pile model.

4.2. Change Rules for the Bearing Capacity of a Single Pile at Different Consolidation Stages. According to the relationship between the compressive modulus and the consolidation degree of each soil layer, the value of the elastic modulus of each soil layer at different consolidation stages can be obtained; then, the values of the shear stiffness modulus and the normal stiffness modulus in the contact parameters of piles and soil in each soil layer can be obtained by the corresponding proportionality coefficient. The ultimate shear strength is related to the ultimate lateral resistance, and the ultimate lateral resistance is mainly related to the internal friction angle of the soil. The ultimate shear strength of the pile-soil contact can be obtained by the ratio of the internal friction angle to the degree of consolidation.

The ultimate bearing capacity of a single pile is analyzed and evaluated by measuring the settlement or horizontal deformation of the top of the pile in the process of grading loading. According to the preliminary design requirements, the vertical bearing capacity of a single pile is controlled by the vertical displacement of the pile top reaching 40 mm, and the horizontal bearing capacity of a single pile is controlled by the horizontal displacement of the pile top reaching 6 mm. MIDAS/GTS NX is used to simulate the staged loading process of the pile, and the bearing capacity is recorded and analyzed when the displacement reaches the control value under each stage load. Figures 10 and 11 show the relationships between the vertical and horizontal bearing capacities of a single pile and the degree of consolidation.

Figures 10 and 11 illustrate that the vertical bearing capacity basically conforms to a linear growth relationship with the degree of consolidation. The vertical bearing capacity of a single pile increases rapidly with the consolidation of the soil. When the degree of consolidation is 80%, the bearing capacity is increased by approximately 1.8 times the value when the degree of consolidation is 0. The horizontal bearing capacity of a single pile shows nonlinear growth with the degree of consolidation. When the degree of consolidation is in the range of 10~50%, the horizontal bearing capacity of a single pile does not increase noticeably with the degree of consolidation. However, when the degree of consolidation reaches 60%, the growth rate becomes faster, and the growth rate is approximately twice that of the original. When the degree of consolidation is 80%, the horizontal bearing capacity is approximately 1.7 times higher than that of the degree of consolidation 0, which is slightly smaller than that for the vertical bearing capacity.

5. Differential Settlement Rules of the Intersecting Buildings

5.1. 3D Numerical Analysis Model of Sluice and Its Adjacent Structures. A three-dimensional numerical analysis model of sluice, seawall, cofferdam, and foundation soil with 91458 hexahedral or triangular-prism solid elements, 5290 beam elements, and a total of 110555 nodes, as shown in Figures 12–14, is established according to the structural shapes and construction process. In the model, the pile foundation at the bottom of the empty box of the sluice chamber and retaining wall is considered, and the pile contact element and the pile tip element are adopted for the pile foundation and soil. Coulomb frictional contact elements are installed between the empty box wing wall and sluice box culvert, between the sluice box culvert and sluice pier, and between the sluice and seawall. The filling and demolition of the cofferdam and the filling of the embankment are also considered.

The Mohr–Coulomb model is used for the soil material, and the linear-elastic constitutive model is used for the sluice, seawall, and cofferdam. The elastic modulus of sluice concrete is 30 GPa, Poisson's ratio is 0.2, and the bulk density is 24 kN/m^3. The elastic modulus of the seawall and cofferdam is 100 MPa, Poisson's ratio is 0.25, and the bulk density is 19.11 kN/m^3. The friction parameter is 0.4 for concrete and concrete and 0.6 for concrete and seawall.

The simulation schedules for the sluice and its adjacent structures are as follows: (1) initial geostress field analysis; (2) cofferdam construction; (3) parameter adjustment of vacuum-surcharge preloading foundation treatment; (4) pile foundation construction at the bottom of the sluice; (5) main body construction of the sluice; and (6) construction of both sides of the seawall and removal of the cofferdam.

5.2. Variation Rules for Open Gap at Different Parts of the Sluice. To study the variations in differential settlement of the sluice with consolidation degree, the soil parameters and contact parameters at each consolidation stage are the same as those for the single pile bearing capacity analysis. The parameters for when the degree of consolidation is 0 are used in the initial stress analysis, and the soil parameters for different degrees of consolidation and pile-soil contact parameters are changed by applying boundary conditions in MIDAS/GTS NX at subsequent construction stages. Figures 15 and 16 show the deformation of sluice and

Table 4: Characteristics of pile end characteristics and pile-soil contact parameters.

Name	Thickness (m)	Ultimate shear strength (kN/m^2)	Shear stiffness modulus (MN/m^3)	Normal stiffness modulus (MN/m^3)	Pile tip bearing capacity (kN)	Pile tip spring stiffness (kN/m)
Contact 1	1	65.94	390	3900	—	—
Contact 2	1	103.62	975	9750	—	—
Contact 3	1	75.36	834.6	8346	—	—
Contact 4	1	103.62	412.5	4125	—	—
Contact 5	1	178.98	731.25	7312.5	—	—
Pile tip element	—	—	—	—	863.5	200960

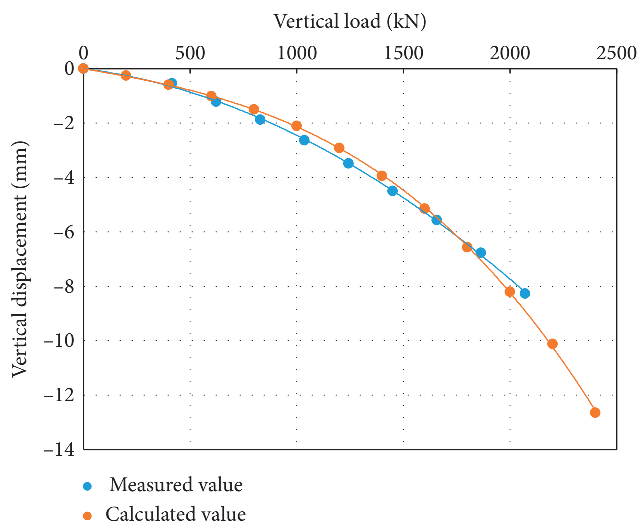

Figure 8: Relationship curve for vertical load and displacement.

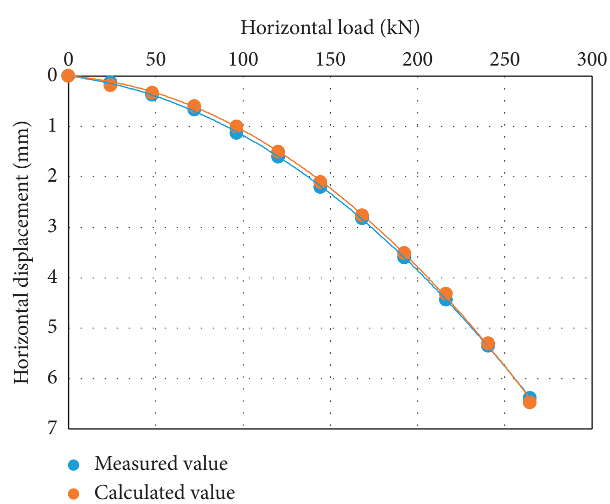

Figure 9: Relationship curve for horizontal load and displacement.

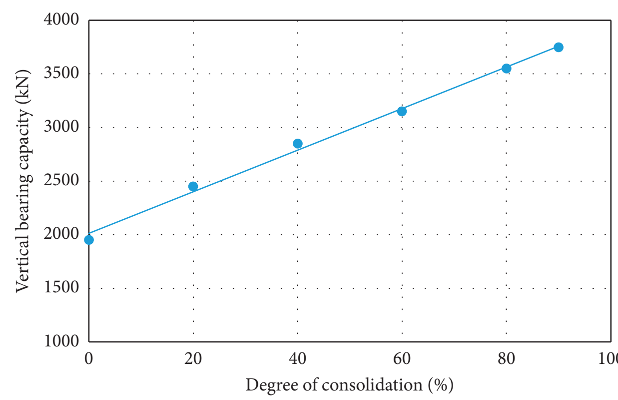

Figure 10: Relationship between vertical bearing capacity and degree of consolidation.

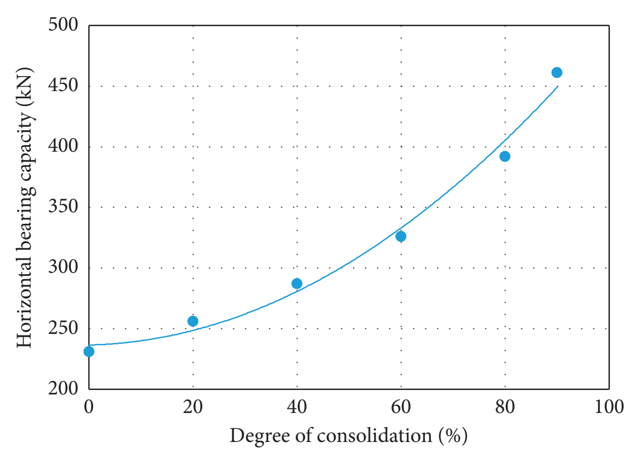

Figure 11: Relationship between horizontal bearing capacity and degree of consolidation.

surrounding engineering structures when the degree of consolidation of soil is zero in the initial state, i.e., the maximum deformation. The gaps between structures are shown in Figures 15 and 16. During the process of soil consolidation, the deformation mode is basically unchanged and the gap width is gradually narrowed. Figures 17 and 18 show the schematic diagram of magnified deformation of sluice and pile foundation after completion of construction of the whole engineering structure when the degree of consolidation of soil is 0 and 80%. The relationship between the open gap of different parts of the sluice and the degree of consolidation is shown in Figures 19–21.

Figure 19 shows that the maximum gap width between the empty box wing wall and the sluice box culvert is 1.92 cm when the degree of consolidation is 0, and it is on the offshore side. As the soil is consolidated, the strength of the soil gradually increases and the gap width gradually decreases. When the degree of consolidation is 80%, the gap width is reduced to approximately 0.85 cm. The maximum gap width on the shore side is 1.31 cm, which is reduced to approximately 0.65 cm when the degree of consolidation is

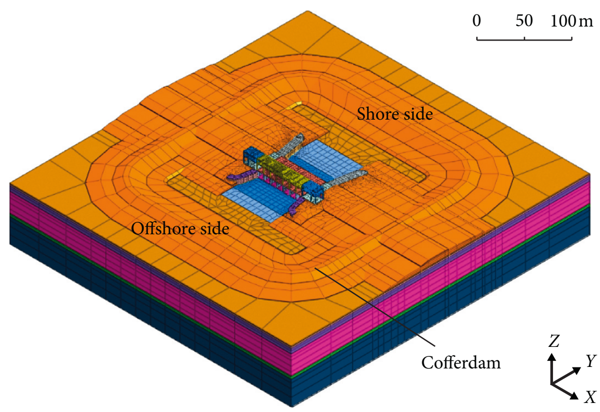

Figure 12: 3D numerical analysis model of sluice and its adjacent structures.

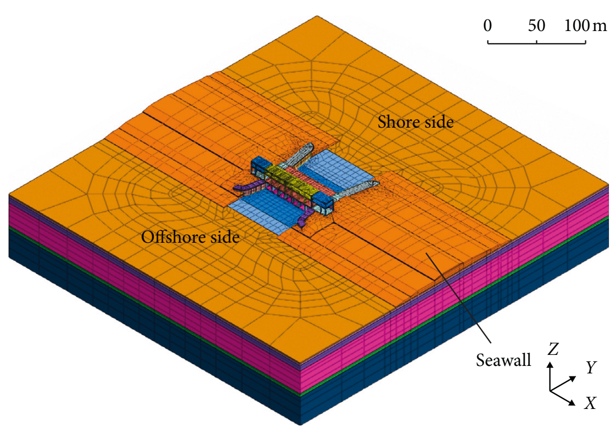

Figure 13: 3D numerical analysis model of sluice and seawall after cofferdam demolition.

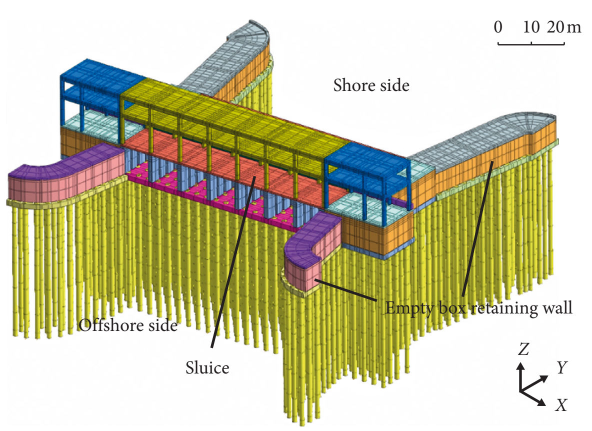

Figure 14: Sluice and its lower piles model.

80%. Figure 20 shows that the maximum gap width between the sluice box culvert and the sluice pier is 3.52 cm. With increasing soil consolidation degree, the maximum gap width is reduced to 1 cm when the consolidation degree is 80%. The width of the gap decreases obviously, which is mainly due to the small difference in the structure between the sluice box culvert and the sluice pier.

Figure 21 shows that the maximum gap width between the sluice box culvert and the seawall is reduced from 5.89 cm

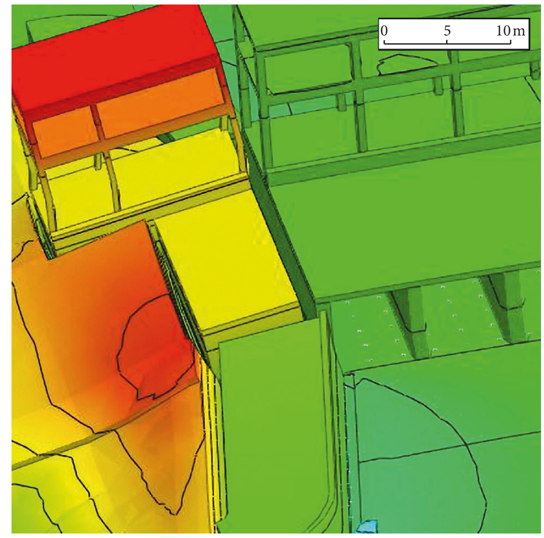

Figure 15: Gaps in a sluice engineering structure (shore side).

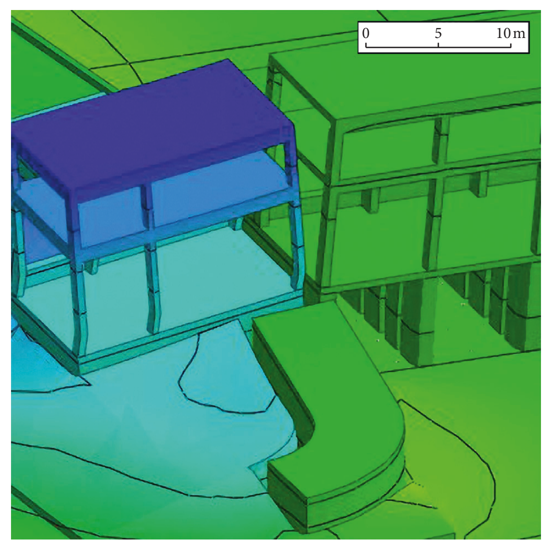

Figure 16: Gaps in a sluice engineering structure (offshore side).

before the soil consolidation to 4.72 cm on the shore side when the consolidation degree is 80% and the maximum gap width on the offshore side is reduced from 4.43 cm to 2.18 cm. Because most of the seawalls on the shore side are filled with closed-air soil and the seawalls on the offshore side are filled with riprap, the deformation modulus of closed-air soil is smaller than that of riprap and the width of the gap on the shore side is significantly larger than that on the offshore side.

6. Conclusions

On the basis of studying the variations in the soil shear strength index and compressive modulus with the degree of consolidation, in this paper, the relationships between vertical bearing capacity, horizontal bearing capacity of a single pile, and the degree of consolidation are studied by establishing a pile-soil interaction model; then, the relationships between the gap width and degree of

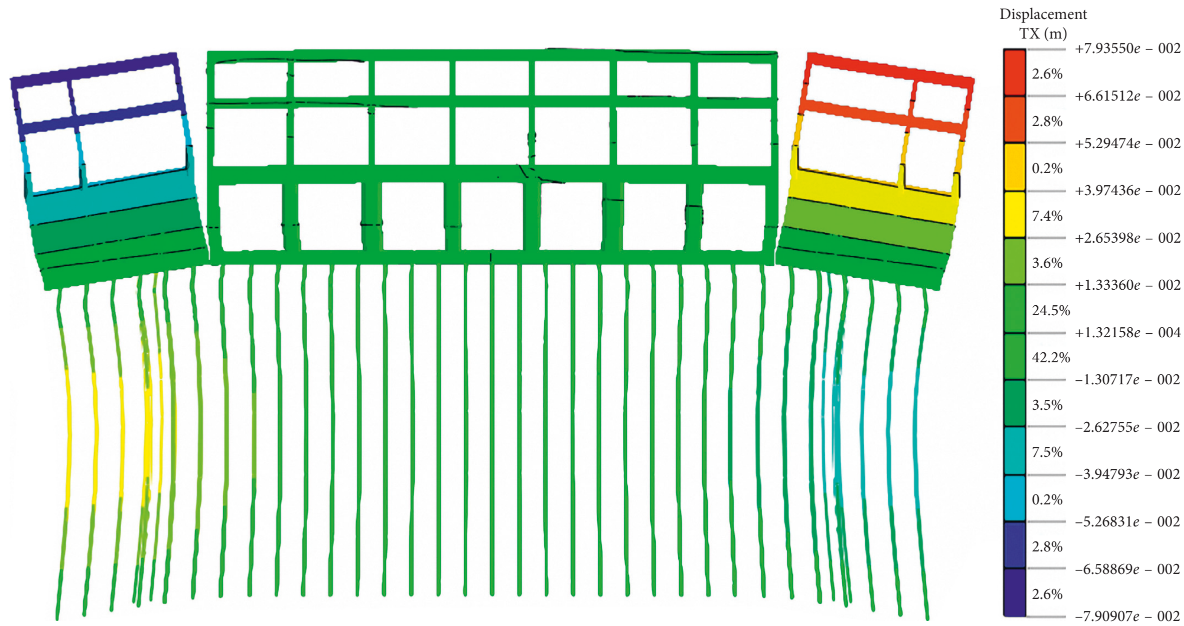

Figure 17: Magnified deformation of the sluice structure and pile (consolidation degree is 0).

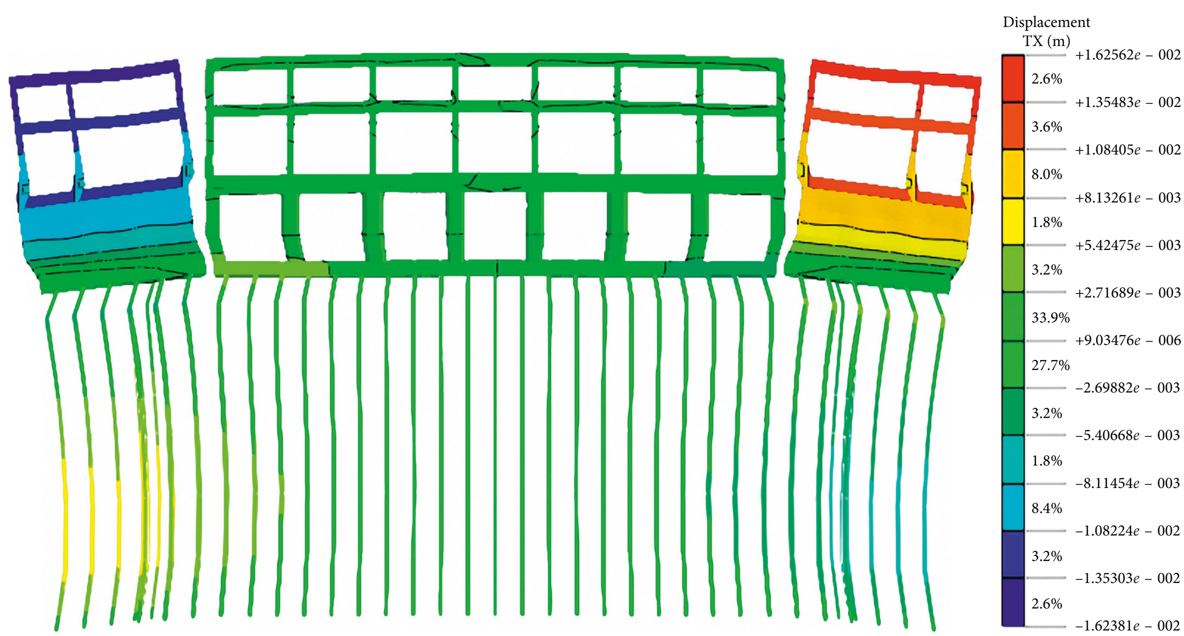

Figure 18: Magnified deformation of the sluice structure and pile (consolidation degree is 80%).

consolidation are obtained by a three-dimensional numerical analysis model of sluice, seawall, cofferdam, and foundation soil. The main conclusions are as follows:

(1) Based on the theoretical study and numerical analysis, the change curves for the physical and mechanical properties of the consolidated soils during vacuum-surcharge preloading are given. With increasing degree of consolidation, the friction angle of the consolidated soils increases obviously and the cohesion decreases slightly. The increase in the compressive modulus of the consolidated soils is obvious, and when the degree of consolidation is greater than 60%, the increase in the compressive modulus of soil becomes faster.

(2) The bearing capacity of a single pile increases with the consolidation of soil around the pile. The vertical bearing capacity of a single pile increases linearly with the consolidation of soil, and the horizontal bearing capacity increases nonlinearly. When the degree of consolidation is 80%, the vertical bearing capacity of a single pile is approximately 1.8 times higher than that when the degree of consolidation is

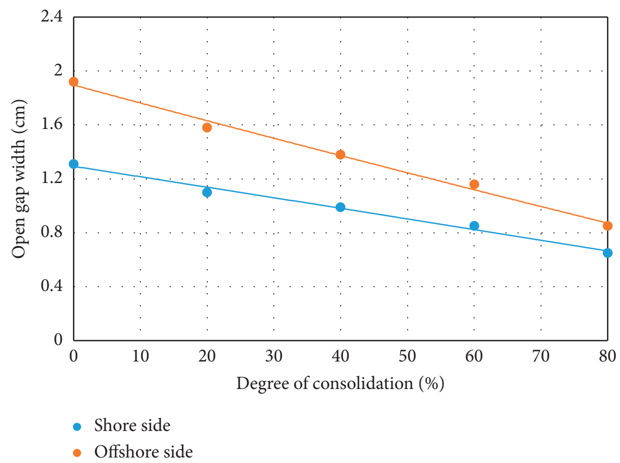

Figure 19: Variation rules for open gap of the empty box wing wall and sluice box culvert.

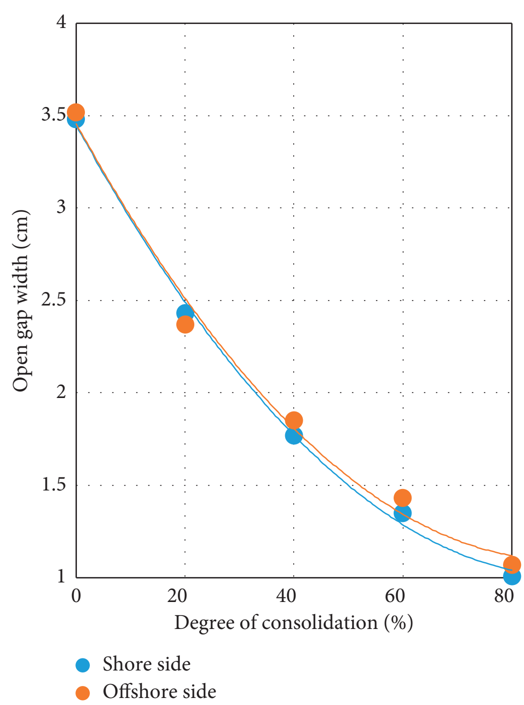

Figure 20: Variation rules for open gap of the sluice box culvert and sluice pier.

0, and the horizontal bearing capacity of a single pile is increased by approximately 1.7 times.

(3) The gap widths between the empty box wing wall and sluice box culvert, between the sluice box culvert and sluice pier, and between the sluice and seawall decrease with increasing degree of consolidation. The width of the gap is also related to the structural type and material.

(4) This paper predicts the variation in the gap width caused by differential settlement between the various structures of the sluice during soft soil cofferdam

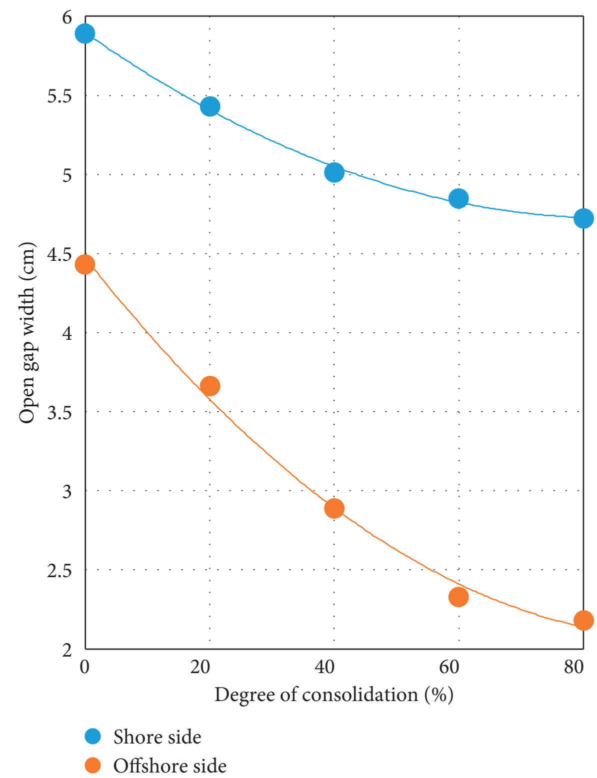

Figure 21: Variation rules for open gap of the sluice box culvert and seawall.

construction. The study provides a method for predicting the bearing capacity of a single pile and evaluating and calculating the differential settlement of intersecting buildings in soft soil beach areas in the preliminary design stage. Thus, this paper has important reference value for saving design time and construction cost and improving engineering construction quality.

Data Availability

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

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

The majority of the work presented in this paper was funded by the National Natural Science Foundation of China (Grant nos. 51679081 and 51709093) and the Fundamental Research Funds for the Central Universities (Grant no. 2016B07614). These financial supports are gratefully acknowledged.

References

[1] Z. Yin and X. Gong, *Example of Foundation Treatment Engineering*, China Water Resources and Hydropower Press, Beijing, China, 2000.

[2] Y. Liu, C. Sun, and S. Li, "Analysis of structural soil's shear strength under arbitrary degree of consolidation," *Applied Mechanics and Materials*, vol. 580–583, no. 20, pp. 774–777, 2014.

[3] W. Bao and X. Zhou, "Experimental study on growth regularity of soil strength with consolidation," *Journal of Yangtze River Scientific Research Institute*, vol. 18, no. 4, pp. 29–32, 2001.

[4] Q. He, W. Leng, and L. Wei, "Experimental study on relationship between soft soil's shear strength and degree of consolidation," *Journal of Railway Science and Engineering*, vol. 2, no. 2, pp. 51–55, 2005.

[5] C. Mu and B. Li, "Dynamic evolution pattern of compressive modulus of soft clay," *Journal of Civil, Architectural and Environmental Engineering*, vol. 31, no. 4, pp. 49–54, 2009.

[6] Z. Guan, S. Chen, M. Huang, T. Deng, and G. Guo, "Study on shear strength and compressive modulus of soil in soft ground improvement," *Chinese Journal of Underground Space and Engineering*, vol. 11, no. 1, pp. 216–221, 2015.

[7] R. P. Chen, W. H. Zhou, and Y. M. Chen, "Influences of soil consolidation and pile load on the development of negative skin friction of a pile," *Computers and Geotechnics*, vol. 36, no. 8, pp. 1265–1271, 2009.

[8] K. Chatterjee and D. Choudhury, "Analytical and numerical approaches to compute the influence of vertical load on lateral response of single pile," *Japanese Geotechnical Society Special Publication*, vol. 2, no. 36, pp. 1319–1322, 2016.

[9] J. L. Zhou, "Construction of sluice on the soft clay foundation," *Journal of Hydraulic Engineering*, vol. 2, pp. 10–18, 1966.

[10] J. Liu, X. Feng, and X. Liu, "Sediment consolidation settlement of Chengbei Sea area in the northern Huanghe River subaqueous delta, China," *Chinese Journal of Oceanology and Limnology*, vol. 35, no. 3, pp. 693–703, 2016.

[11] G. X. Wang, Z. X. Zhou, and L. Chao, "Study on application of vacuum preloading in treatment of soft soil foundation in the port reclamation area," *Coastal Engineering*, vol. 36, no. 4, pp. 44–52, 2017.

[12] H.-X. Wang, C.-H. Yang, F. Chen, and H.-J. Mao, "Analysis of the changing rule of shear strength indexes of soft soil with consolidation degree," *Rock and Soil Mechanics*, vol. 35, no. S1, pp. 106–112, 2014.

[13] Y. Lou, "Variation of consolidation coefficient for soft soil in preloading improvement," *Hydro-Science and Engineering*, vol. 4, pp. 46–50, 2006.

[14] J. Li, B. Hong, X. Liu, and G. He, "Research on calculating post-construction settlementof road foundation based on dynamic compressive modulus," *Sichuan Building Science*, vol. 40, no. 4, pp. 197–200, 2014.

[15] C. Zhou, C. Lin, L. Lin, and X. Yang, "Research on dynamic evolution law of compression modulus of soft clay under external loads," *Rock and Soil Mechanics*, vol. 31, no. 07, pp. 2040–2044, 2010.

[16] J. Huan and J. Zheng, *Geological Engineering Handbook*, China Architecture & Building Press, Beijing, China, 5th edition, 2018.