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Research Article

Research on the Effective Control of Ground Settlement during Double-Layered Foundation Pit Dewatering Based on Seepage Control-Recharge Coupling Model

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This study focuses on the settlement of buildings around the foundation pit caused by foundation pit dewatering. Within the study context, a test is conducted on the control of ground settlement during double-layered foundation pit dewatering based on the seepage control-recharge coupling effect. Moreover, a large indoor seepage test device is developed to accurately simulate in-situ three-dimensional seepage conditions of double-layer foundations. The study results showed that compared to the antiseepage conditions, upon the additional recharge, the head of the upper row of the pressure measuring tubes outside the foundation pit is raised by nearly 10.7%, and the water level of the lower row of pressure measuring tubes is raised by about 3.1%. Additionally, the head of the outer side of each pressure measuring tube is higher than that of the inner side by about 2.75% on average, indicating that the recharge outside the pit can effectively increase the head height in the area above the soil layer at the bottom of the recharging well outside the foundation pit and reduce the settlement of the building outside the foundation pit. The numerical calculation of the settlement outside the pit using FLAC3D software further confirms the effect of the seepage control-recharge coupling model on the ground settlement during foundation pit dewatering. The research results are important for the infiltration deformation and foundation settlement control in composite foundations precipitation.

1. Introduction

For a typical double-layer foundation, the upper soil is mostly the weak permeable layer with the permeability coefficient of 10^{-4}~10^{-6} cm/s, and the lower soil is mostly the strong permeable layer with the permeability coefficient of 10^{-1}~10^{-2} cm/s. The foundation in the middle and lower reaches of the Yangtze River is mostly distributed with such double-layer composite foundation soil.

During the dewatering of the double-layer foundation pit, the movement of silty fine sand particles in the permeable layer leads to the rapid drop of water level, which leads to the rapid dissipation of soil pore pressure. With the rapid dissipation of pore pressure, the effective stress of soil mass increases instantaneously, which leads to uneven ground settlement, seriously threatening the safety of surrounding buildings [1–4].

To solve the problem of differential ground settlement caused by foundation pit dewatering, the water level outside the pit is usually raised by setting impermeable walls to mitigate the influence of dewatering on ground settlement and improve the seepage field morphology to control the development of seepage deformation [5, 6]. The foundation pit dewatering and recharge can raise the groundwater level around the well and maintain the soil's effective stress, thus reducing the differential ground settlement and weakening the influence of dewatering on the surrounding buildings [7, 8].

Table 1: Basic physical and mechanical parameters of the test earth materials.

Soil sample	Moisture content (%)	Liquid/plastic limit (%)	Permeability coefficient	Dry density (g/cm^3)	Proportion
The surface layer of clay	27.6	38.9/19.6	6.1×10^{-6} cm/s	1.6	2.71
The lower layer of sand	30.7	—	1.3×10^{-2} cm/s	1.4	2.67

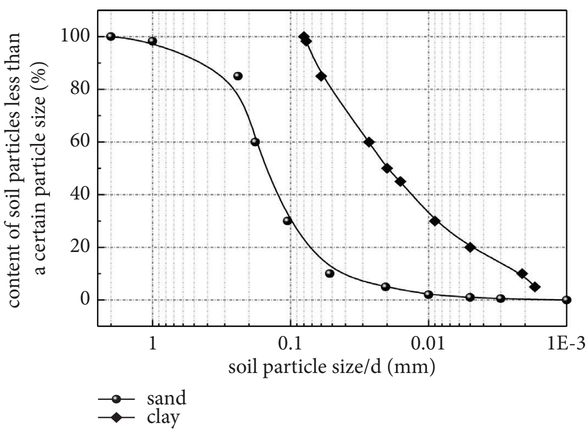

Figure 1: Grading curves for clay and sand used in the test.

Existing studies have mostly focused on a single technology of impermeable wall or recharge raising dewatering level to mitigate the settlement. Lots of scholars have studied the seepage control mechanism of suspended impermeable walls using methods such as indoor sand tank models and numerical calculations [9–12]. The recharge technology has been applied to engineering since the 18th century. Currently, river recharge is being used in many European and American countries to solve the problem of declining groundwater [13]. Generally, irrigation technology was introduced in China in the late 20th century. Zhao simulates and analyzes the control effect of the recharge well arrangement position and inclination angle on the settlement of structures outside the pit [14]. Liu et al. [15] showed that artificial groundwater recharge with variable pressure and flow can effectively realize the dual control of groundwater level and ground settlement. W. L. Li and Y. T. Li used rapid surface water recharge technology to study the water shortage situation and the ecological environment effect in a reservoir area [16]. The stability of foundation pits and surrounding buildings are investigated by using hydraulic connections among aquifers [17]. Huang and Xu conducted a three-dimensional numerical simulation on the process of deep foundation pit dewatering and recharge, analyzed and discussed the feasibility and accuracy of the simulation, and studied the recharge effect of different recharge methods and the effect of recharge on the change in water level outside the pit and ground settlement [18].

Nowadays, many scholars believe that the requirements for controlling the settlement outside the pit cannot be met by only setting up an impermeable wall or applying recharging technology [19]. In particular, the engineering construction under complex geological environment conditions is a challenge to the soil stability [20–22]. Therefore, many studies have been conducted on the feasibility of combining antiseepage and recharge technologies. Some scholars proposed an integrated design method of foundation pit support and engineering dewatering and conducted application research from the perspectives of optimizing waterproof curtains, dewatering process, comprehensive monitoring of ground settlement, and artificial recharge to achieve improved mitigation of ground settlement [23]. These studies provide a preliminary understanding of the governance of settlement through the integration of impermeable walls and recharge in foundation pit dewatering. However, in the current results, there is a lack of systematic research on the recharge-antiseepage coupling mechanism for foundation pits in dewatering construction. The mechanism for antiseepage and settlement of the foundation under foundation pits dewatering-recharge-antiseepage coupling action has not been clarified.

This paper relies on the expansion and reconstruction project of the Qinhuai River Shiplock. The Qinhuai River Shiplock is located in the lower reaches of the Qinhuai River, about 2 km away from the river entrance. It is the only river gate Shiplock connecting the Yangtze River trunk line and Nanjing inland waterway and is an important infrastructure for water transportation in Nanjing. The site geological conditions are the upper clay and muddy clay, and the lower part is a deep and strong permeable sand layer and silty sand layer. The Shiplock foundation pit is excavated to the top surface of the sand layer. In order to simulate the three-dimensional seepage conditions of a construction site, this paper proposes a model for site geological conditions, and a coupling test for double-layered foundation pits dewatering, seepage control of impermeable wall, and recharge of recharging well is carried out. Through the observation of the water level for each pressure measuring tube in the model, the laws for groundwater level variation at different soil layer depths under two working conditions of dewatering-seepage control and dewatering-seepage control-recharge are investigated. Based on the laboratory test, FLAC3D V4.0 software is used for numerical analysis, and the calculation model is established using the actual terrain and its field conditions. The three-dimensional fluid-solid coupling calculation program is used to analyze and study the influence on the seepage field and the settlement outside of the pit by setting up the impermeable wall and recharging wells in the foundation pit dewatering. The relevant research findings are important for controlling seepage deformation of composite foundations.

2. Soil Samples and Models

2.1. Soil Samples. The test soil samples were taken from the foundation soil of the Qinhuai River Shiplock Project site in the middle and lower reaches of the Yangtze River. The surface layer was clay with weak water permeability, and the lower layer was the sand layer with strong water

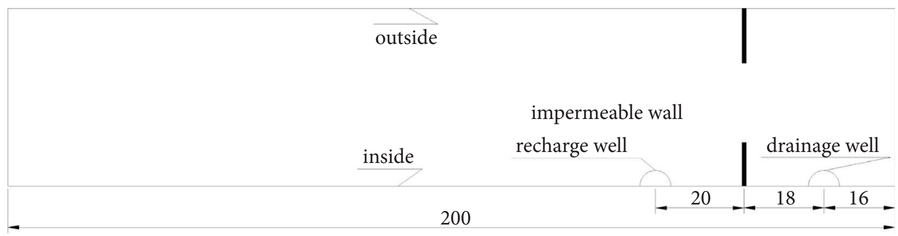

Figure 2: Schematic diagram of indoor seepage groove structure (unit: cm).

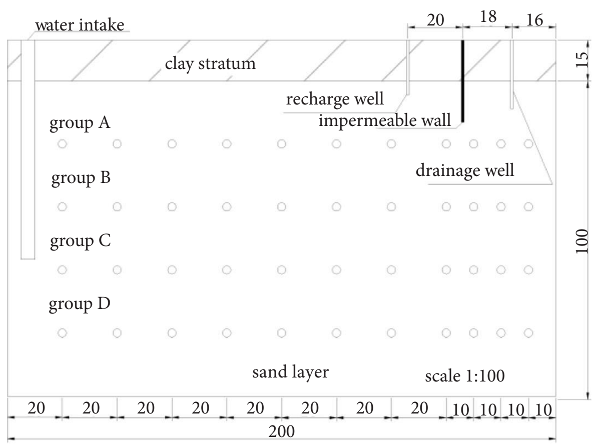

Figure 3: Schematic diagram of the recharging well, impermeable walls, and dewatering well (unit: cm).

permeability. In this study, a series of tests were conducted to determine the basic properties of the two kinds of earth materials. Table 1 shows the relevant physical and mechanical parameters.

The particle size analysis was carried out on the clay's surface layer and the sand's lower layer, and the grading curves are shown in Figure 1. It can be seen that the silty clay in the surface layer is uniformly graded and presents a wide range of particle sizes; hence, it is easy to form a dense confined aquifer on such soil. Due to the nonuniform gradation of silt in the lower layer and the smaller bite force between particles, it is easy to lose fine particles under the water flow action, leading to the seepage failure of the foundation soil.

2.2. The Physical Model in the Tests. In order to simulate the actual seepage conditions, a three-dimensional seepage testing device for 1 : 100 reduced site geological conditions was developed. Figure 2 shows the specimen's size and distribution. For the convenience of observation, the model material was made of 1-cm-thick plexiglass. The model groove has a length of 200 cm, a width of 10 cm, and a height of 115 cm. The two long sides of the model groove simulate the axes of the dewatering and recharging wells and the vertical lines of the two adjacent dewatering well axes, respectively. A 10 cm diameter inlet was set at the left end, and holes were drilled uniformly on the tube wall and wrapped with a 100-mesh filter to simulate the underground water outside the pit. The right end simulates the east-west axis of the foundation pit.

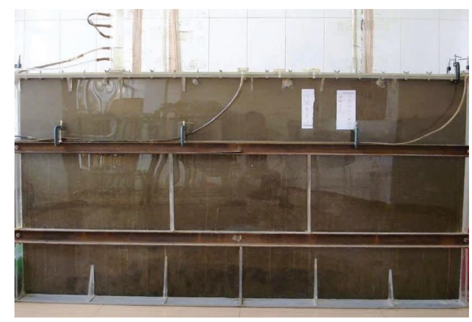

Figure 4: Photos of the experimental model.

A dewatering and recharging well were set 16 cm and 54 cm away from the right side of the model groove. PVC pipes with a 2 cm diameter were used to simulate the dewatering and the recharging wells, and 100-mesh filters were wrapped around the outside of the PVC pipes. The dewatering and recharging wells were set on the side wall of the model groove, as shown in Figures 3 and 4. An impermeable wall was set 34 cm away from the model groove's right side, and a plexiglass plate was selected to simulate impermeable materials. The area beyond the axis of the dewatering and recharging wells is called the outer side of the strata, and the relative side within the axis of the dewatering and recharging wells is called the inner side of the strata.

In order to measure the water level variation along the route, 88 pressure measuring tubes were laid out in a row at 20, 40, 60, and 80 cm from both sides of the models' top. A saturation device port was set at the bottom of the model to saturate the soil samples before the test began. At the same time, channel steel was set on both sides of the model to prevent the deformation of the model groove.

2.3. Test Process Description. During sample preparation, the dry density was controlled to be consistent with that in the field. The clay on the surface layer was divided into two layers, and the lower silt was divided into eight layers to be filled into the model, layered compacted, and surface scrapped. From the bottom of the groove, the water gradually infiltrated into the soil to saturate it. After 24 hours of saturation, the water storage container gradually changed from low to high to facilitate gas emission from the soil. Thereafter, the upstream head gradually increased to start the test, and lastly, the dewatering-seepage control and dewatering-recharge-seepage control tests were initiated. The specific process here is to open the outlet of the dewatering well so that dewatering begins to occur in the

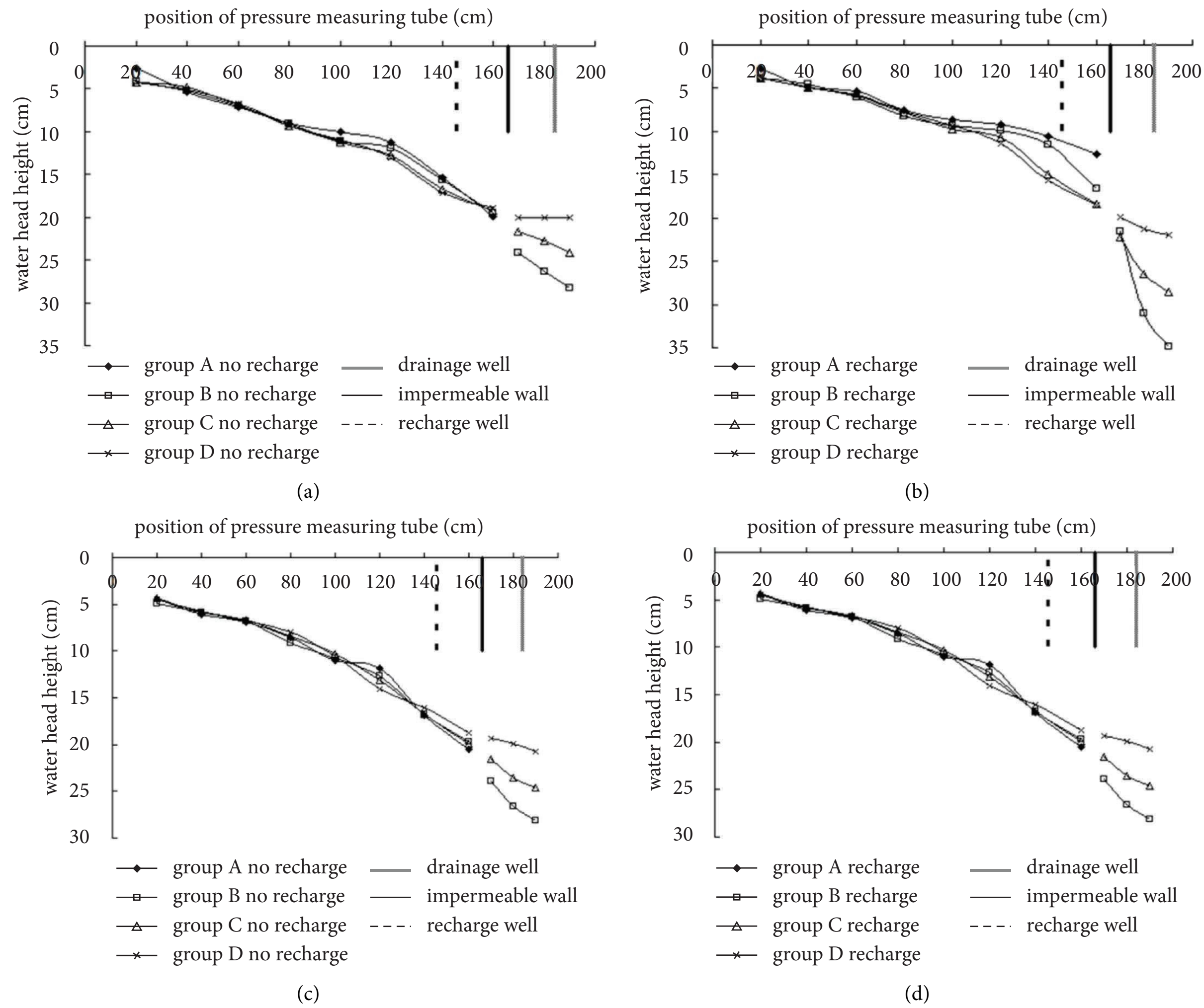

Figure 5: Variation laws on groundwater level in the stratum under two working conditions with and without recharge. (a) Variation of water level on the outside (the side with wells) with distance excluding recharging. (b) Variation of water level on the outside (the side with wells) with distance under recharging. (c) Variation of water level on the outside (the side with no well) with distance excluding recharging. (d) Variation of water level on the outside (the side with no well) with distance under recharging.

foundation pit and, meanwhile, record the changes of head and seepage flow along the route until the data are stable. The process of completing the dewatering and seepage control tests (the impermeable wall was laid out in the device) lasted two days. The water outlet valve of the dewatering well and the water inlet valve of the recharging well were opened, and the changes in the head and seepage flow along the route were recorded until reaching stable data to complete the dewatering-recharge-seepage control test.

3. Test Results and Analysis

Figure 5 shows the variation laws of groundwater levels in the strata during double-layered foundation pit dewatering under the two working conditions: (1) adding recharging wells for recharge; (2) not adding recharging wells while applying impermeable walls for seepage control. The outer side refers to the axis side of the dewatering well and the recharging well, while the inner one refers to the relative side of the axis in the dewatering and recharging wells. It can be seen that in the process of dewatering and seepage control of a double-layered foundation, the head height of the pressure measuring tube in the same column on the left side of impermeable walls does not vary considerably when the recharge is not started. After carrying out the recharge, the head height of the pressure measuring tubes in the same column on the left side of the impermeable walls shows the following characteristics: (1) the head height of the two pressure measuring tubes rows (A and B) above the recharge depth is significantly higher than that of the two pressure measuring tubes rows (C and D) below the recharge depth; (2) the head height of the pressure measuring tubes in Row A is higher than that in Row B, and the head heights of the pressure measuring tubes in Row C and Row D are the same. Before and after recharge, the head at A in the upper row of the pressure measuring tubes is raised by nearly 10.7%, and the water level at C and D of the lower row in the pressure measuring tubes is raised by about 3.1%. This indicates that the head height in the area above the soil layer at the bottom of the recharging well can be effectively raised when the

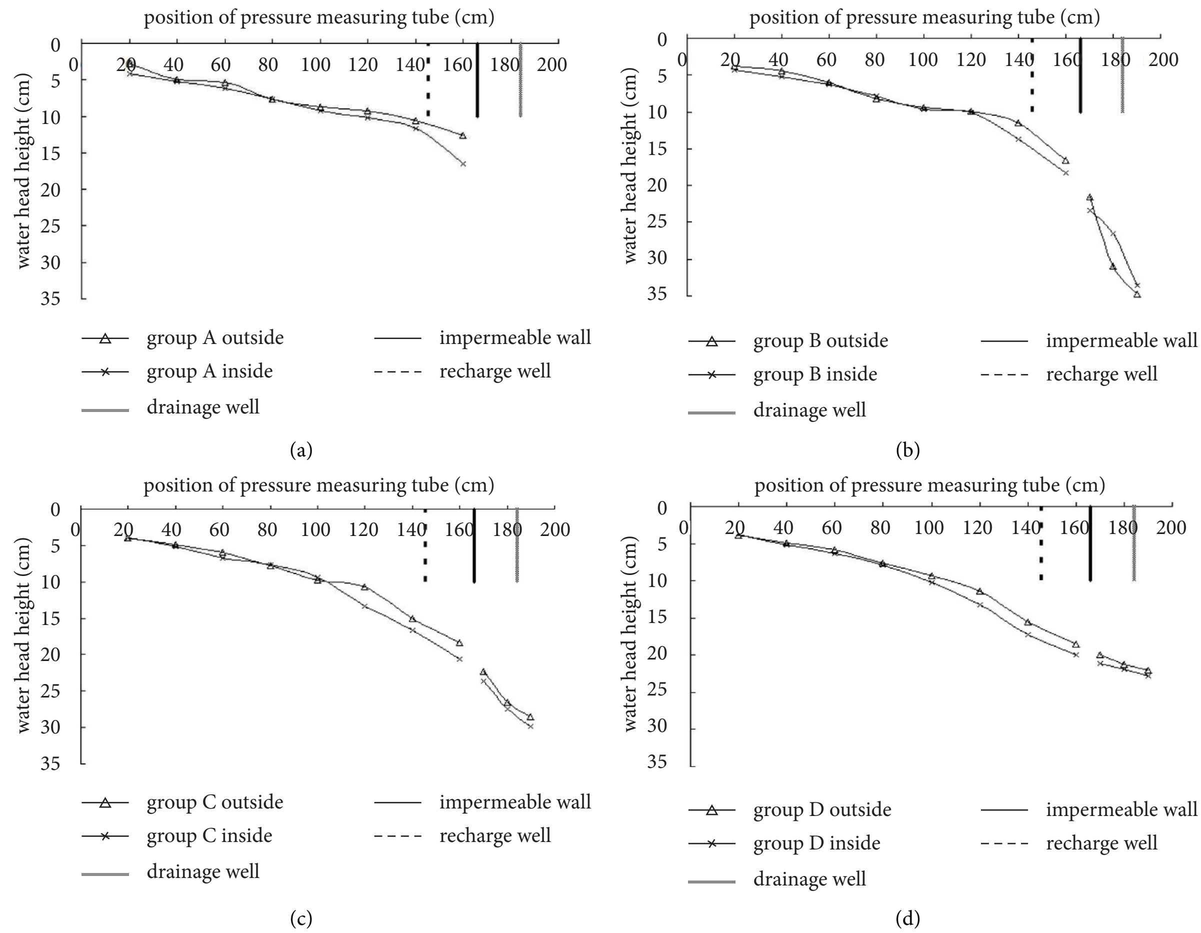

Figure 6: The variation laws on the water level during dewatering-seepage control-recharge coupling. (a) Variations in the heads inside and outside the pressure measuring tubes in row A with distance under recharging. (b) Variations in the heads inside and outside the pressure measuring tubes in row B with distance under recharging. (c) Variations in the heads inside and outside the pressure measuring tubes in row C with distance under recharging. (d) Variations in the heads inside and outside the pressure measuring tubes in row D with distance under recharging.

double-layered foundation dewatering-seepage control construction, as well as recharge, is carried out, and the shallower the soil layer is, the more significantly the head is raised.

Furthermore, the variation laws on the water level of each pressure measuring tube row in the foundation pit dewatering-seepage control-recharge are plotted in Figure 6. According to the changes in water level inside and outside the four rows (A-D) of pressure measuring tubes, the water level outside each pressure measuring tube after recharge is about 2.75% higher than the elevation of the water level inside it. Hence, it can be concluded that (1) the technology with the integration of dewatering-seepage control and recharge has a better effect in lifting the head of the strata outer side than in lifting the head of the strata inner side; (2) recharging a well plays a vital role in raising the head outside the pit during foundation pit dewatering, and the closer it is to the well, the more significant the effect of raising the head. According to the double-layered foundation dewatering-seepage control-recharge laboratory model experiments, the spatial distribution of groundwater level and the head of the hydraulic boundary in the center of the two well points can be analyzed, which has guiding significance for well point layout in engineering.

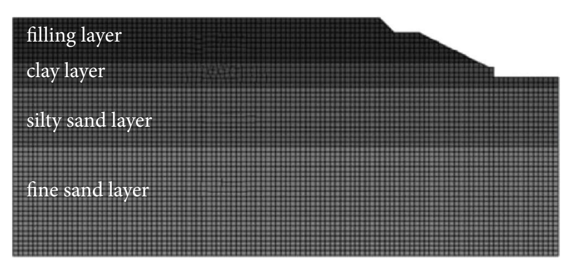

Figure 7: Distribution grid of each soil layer.

4. Numerical Calculation and Analysis

Based on the laboratory test, FLAC^{3D} V4.0 software was used for numerical analysis, and an estimation model was developed using the actual field terrain and boundary conditions. A three-dimensional fluid-solid coupling program was used to analyze and study the influence on the seepage field and the settlement outside the pit by setting

Table 2: Settlement under two working conditions.

Monitoring points	Settlement of monitoring points (mm)		
	Calculated value		Measured value
	Dewatering-seepage control	Dewatering-seepage-control-recharge	
A1	23.30	13.93	
A2	27.18	16.58	16.64
A3	31.41	19.43	19.38
A4	35.72	22.28	21.43
A5	39.71	24.78	

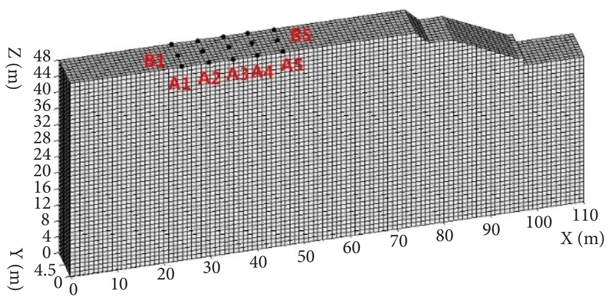

Figure 8: The location graph for monitoring points.

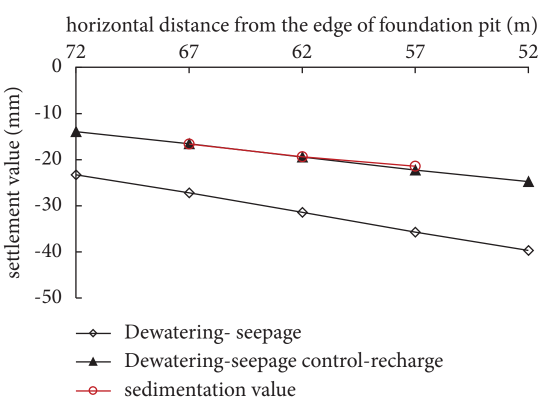

Figure 9: Settlement curves for the monitoring points under the two working conditions.

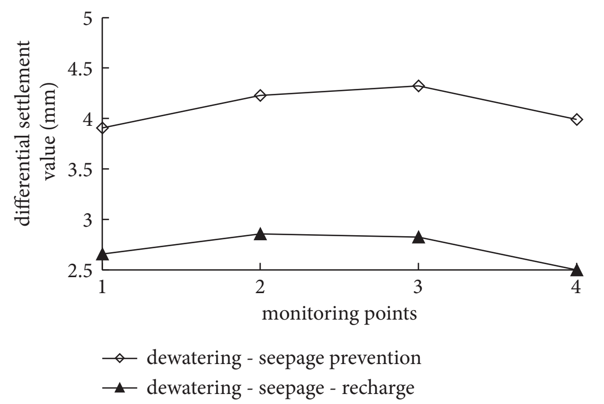

Figure 10: Differential settlement curves for adjacent monitoring points under the two working conditions of dewatering-seepage control and dewatering-seepage control-recharge. Note: abscissa 1 is the settlement difference between A1 and A2; 2 is the settlement difference between A2 and A3; 3 is the settlement difference between A3 and A4; 4 is the settlement difference between A4 and A5.

impermeable walls and recharging wells in the foundation pit dewatering system.

In the calculation process of this model, the constraint condition of the bottom boundary of the model is that the horizontal and vertical displacements are always zero. The left and right boundary conditions of the model are that only vertical displacement does not occur in horizontal displacement. The left part of the model is defined as the constant water level, and the average water level of the Qinhuai River measured on-site is used as the high water level. The actual project ground elevation of −40.0 m is selected as the bottom surface of the calculation model, and the top surface elevation of +8.0 m filling layer is selected as the top surface of the calculation model. In the model, the interface among soil layers is simplified by using straight-line layering. The thickness of the filling layer is 6.5 m, the thickness of the clay layer is 4.1 m, the thickness of the silty sand layer is 12.5 m, and the thickness of the fine sand layer is 29.1 m, as shown in Figure 7.

Biot initially assumed that the soil skeleton is a linear elastic body and obeyed the generalized Hooke's law, so the physical equation is as follows:

$$\begin{cases} \varepsilon_x = \dfrac{1}{E'}\left[\sigma_x' - \nu'\left(\sigma_y' + \sigma_z'\right)\right], \\ \varepsilon_y = \dfrac{1}{E'}\left[\sigma_y' - \nu'\left(\sigma_x' + \sigma_z'\right)\right], \\ \varepsilon_z = \dfrac{1}{E'}\left[\sigma_z' - \nu'\left(\sigma_x' + \sigma_y'\right)\right], \\ \gamma_{yz} = \dfrac{\tau_{yz}}{G'} = \dfrac{\tau_{yz}\cdot 2\left(1+\nu'\right)}{E'}, \\ \gamma_{zx} = \dfrac{\tau_{zx}}{G'} = \dfrac{\tau_{zx}\cdot 2\left(1+\nu'\right)}{E'}, \\ \gamma_{xy} = \dfrac{\tau_{xy}}{G'} = \dfrac{\tau_{xy}\cdot 2\left(1+\nu'\right)}{E'}. \end{cases} \tag{1}$$

The monitoring points in the figure are the key protected Shiplock management office building area. In the calculation model, five monitoring points A1, A2, A3, A4, and A5 are selected according to the different horizontal distances from the foundation pit, and the settlement of these five observation points is compared.

Table 2 shows the calculated settlement of each monitoring point under the two different conditions of dewatering-seepage control and dewatering-seepage control-recharge based on the numerical simulations. Besides, it presents the actual settlements for the three monitoring points A2, A3, and A4.

According to Table 2, the maximum deviation between the measured and the calculated value for the settlement at the three monitoring points A2, A3, and A4 is about 4%, indicating that it is feasible to calculate the settlement using the numerical approach.

The settlement curves for each monitoring point under the two working conditions of dewatering-seepage control and dewatering-seepage control-recharge were obtained numerically, as shown in Figure 8. In addition, the differential settlement curves of two adjacent monitoring points are plotted, as shown in Figure 8, in which abscissa 1 denotes the settlement difference between A1 and A2, abscissa 2 denotes the settlement difference between A2 and A3, abscissa 3 denotes the settlement difference between A3 and A4, and abscissa 4 denotes the settlement difference between A4 and A5.

According to Figures 9 and 10, performing the coupling action mode of dewatering, seepage control, and recharge by setting impermeable walls and recharging wells during deep foundation pit dewatering can effectively reduce differential settlement outside the pit. The closer the soil is to the impermeable walls and recharging wells, the more obvious the coupling effect on it and the smaller the soil differential settlement.

5. Conclusion

This paper carries out a test on the control of ground settlement during double-layered foundation pit dewatering based on the seepage control-recharge coupling model. By observing the water level of each pressure measuring tube in the model, the following conclusions are drawn:

(1) The integrated combination of the cutoff wall and reinjection well in the dual foundation can effectively prevent the groundwater level behind the cutoff wall from lowering during dewatering. Compared with the dewatering antiseepage conditions, after adding reinjection, the water head of the upper piezometer outside the foundation pit rises by nearly 10.7%, and the water level at C and D of the lower piezometer rises by about 3.1%; the water head on the outside of each piezometric pipe is about 2.75% higher than that on the inside.

(2) The differential settlement value outside the pit when the cutoff wall and reinjection well are set is smaller than that when the direct precipitation is used, which can reduce the uneven settlement outside the pit. The closer the cutoff wall and reinjection well are, the smaller the uneven settlement is, which can effectively reduce the impact of foundation pit precipitation on surrounding buildings. The reinjection well plays an obvious role in raising the water head outside the pit to reduce the surface settlement outside the pit in foundation pit dewatering, and the closer the well is, the more obvious the effect of raising the water head is.

(3) The numerical results are in good agreement with the model test results. The numerical analysis shows that the uneven settlement outside the pit can be controlled effectively by adding recharge at the same time of precipitation and seepage prevention. The setting of an impermeable wall and reinjection well can effectively reduce the settlement outside the pit. The setting of impermeable wall and reinjection well simultaneously during the antiseepage process of the deep foundation pit can greatly reduce the settlement outside the pit

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

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