

Article

Deformation Behavior of Diaphragm Walls and Ground Surface During Excavation of a Circular Deep Foundation Pit Considering Coupled Dewatering and Recharge Effects

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Abstract

Few studies have focused on the deformation of ultra-deep circular foundation pits under the combined effects of dewatering and recharge. Therefore, a case of an ultra-deep circular foundation pit in a soft soil area was selected to investigate the mechanisms of groundwater variation induced by dewatering and recharge during excavation, and the resulting ground surface and diaphragm wall deformation. The main conclusions are as follows: (1) The model was validated against field measurements, showing good agreement in magnitude and variation trends for both ground settlement and diaphragm wall deformation. (2) With increasing dewatering rate, pore water pressure at the dewatering wells gradually decreased, forming more pronounced drawdown funnels. The reduction in pore water pressure increased soil effective stress, expanded the high-stress zone, and induced ground settlement and lateral displacement of the diaphragm wall, intensifying overall pit deformation. (3) With increasing recharge rate, pore water pressure around the recharge wells gradually increased, forming localized high-pressure zones. Ground surface heave occurred due to buoyancy from the expanded saturated soil zone, while lateral displacement of the diaphragm wall was simultaneously amplified. The affected zone expanded with higher recharge rates, enhancing overall soil deformation around the pit.

Keywords: ultra-deep circular foundation pit; dewatering; recharge; diaphragm wall deformation; ground settlement; finite element analysis



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1. Introduction

Circular deep foundation pits are increasingly applied in underground engineering due to their unique advantages [1,2]. The circular arch effect allows the compressive strength of the structure to be fully utilized. Strong self-stabilization can effectively reduce lateral displacement and deformation of the retaining structure, thereby ensuring structural stability and safety [3]. Currently, foundation pit projects tend to be deeper, larger in scale, and have longer spans, which pose higher requirements for groundwater control. In areas with high groundwater levels, closed impermeable curtains cannot completely prevent

seepage [4,5]. Therefore, dewatering and recharge measures are required to ensure safe and stable construction. However, large-scale and long-term dewatering can cause significant groundwater level decline, leading to secondary issues such as ground settlement, pipeline disturbance, and deformation of adjacent structures [6–9]. Groundwater recharge has been widely applied in deep foundation pit engineering as an effective method to adjust groundwater pressure and mitigate adverse effects caused by dewatering [10,11].

Many studies have been conducted on circular deep foundation pits. For example, Guo et al. (2025) [12] investigated the behavior of a circular foundation pit in plateau alluvial-lacustrine gravel using a three-dimensional physical model test based on similarity theory. The stress response during excavation and the applicability of the developed similar material were revealed. Gao et al. (2020) [13] studied the settlement and displacement of an underground diaphragm wall during circular foundation pit excavation using monitoring data and three-dimensional numerical simulation. Gao et al. (2025) [14] investigated deformation and displacement of a circular foundation pit using monitoring data, full-cycle modeling, and a parameter-checking method, and key deformation stages and critical excavation conditions were identified. The temporal and spatial evolution of deformation, effects of pit diameter and soil thickness on stability, and methods for evaluating deformation control in large and deep pits were demonstrated. However, these studies mainly addressed the effects of excavation on pit deformation, while the influence of dewatering and recharge measures was often neglected. For ultra-deep circular foundation pits constructed near lakes with high groundwater levels and thick soft soil, the combined effects of groundwater variations on the deformation of circular foundation pits during construction have not been realistically reflected in existing research, resulting in a gap with practical engineering conditions.

The effects of dewatering and groundwater recharge on foundation pit deformation have been extensively investigated through field observation [15–17], physical model tests [18,19] and numerical simulations [20,21]. The effectiveness of recharge in restoring groundwater levels and controlling ground settlement has been demonstrated. For example, Yang et al. (2025) [22] studied the effects of dewatering and reinjection on foundation pit deformation through laboratory experiments and theoretical analysis. It was found that dewatering mainly influences surface settlement in the surrounding seepage area, while full-depth inclined reinjection exerts the strongest effect on settlement but minimal influence on diaphragm wall displacement. Wang et al. (2025) [23] conducted field pumping and recharge tests in a super-large deep foundation pit group in Shanghai. Significant deep and surface settlements were observed due to hydraulic connections between aquifers. Recharge was shown to raise groundwater levels and reduce settlement, although vertical variations could not be completely eliminated. Ping et al. (2024) [24] used numerical simulations in Chengdu's Tianfu New Area to study dewatering effects on groundwater and ground settlement in soluble rock formations. Leakage between aquifers was found to significantly affect settlement. Increasing the depth of the waterproof curtain reduced both settlement and leakage, with different critical depths identified for each stage. Wang et al. (2023) [25] used a 3D groundwater flow model to study the influence of geological features on dewatering efficiency in a deep excavation along the Chongjiang River, and found that more aquitard layers improve efficiency, higher clay permeability reduces efficiency, and dewatering is faster when clay layers are located below the riverbed. Wang et al. (2021) [26] used Midas GTS software and field measurements to study a deep foundation pit near the Beijing–Baotou railway, and found that the five-sided water-stop structure formed by cement piles around and at the bottom of the pit prevented consolidation settlement of the adjacent railway subgrade caused by deep dewatering and also reduced lateral displacement of the retaining structure and heave of the pit bottom. Recent studies

have shown that structural deformation responses under complex engineering conditions are closely related to material degradation and restraint mechanisms, as well as coupled soil–foundation–structure interaction [27,28].

Therefore, it is necessary to further investigate the deformation behavior of ultra-deep circular foundation pits under the combined effects of dewatering and groundwater recharge, especially under complex hydrogeological conditions. Compared with previous studies, this study first focuses on an ultra-deep circular foundation pit in a soft soil area with a high groundwater level in Hangzhou. The excavation depth reaches 71.5 m, indicating more complex engineering conditions. Second, a three-dimensional seepage–stress coupled model considering the combined effects of dewatering, recharge, and the supporting structure was established using finite element simulation. Finally, the responses of the pore pressure field, ground surface settlement, and diaphragm wall displacement under different dewatering and recharge rates were analyzed simultaneously. From the perspective of engineering application, a coordinated dewatering–recharge control strategy was proposed, providing a reference for deformation control in similar ultra-deep circular foundation pits.

2. Materials and Methods

2.1. Study Area

The project of an ultra-deep circular foundation pit located in Yuhang District, Hangzhou, was selected as the engineering background of this study. The surrounding ground surface is relatively flat, and the site geomorphologically belongs to the Hangjiahu marine-alluvial plain. The eastern side of the site is adjacent to Xixi National Wetland Park. The terrain in this region is low-lying, with dense river networks and a highly developed surface water system. The shallow groundwater at the site is phreatic pore water, which mainly occurs in the shallow soil layers. The deep groundwater is confined fissure water in the bedrock and is mainly stored in the bedrock strata. The measured buried depth of the confined groundwater head is approximately 21.0 m below the ground surface. The excavation depth of the foundation pit reaches 71.5 m, the excavation area is approximately 702 m², and the total perimeter length is about 90.0 m. The project is therefore classified as a typical ultra-deep and large-scale foundation pit with complex geological conditions and very strict deformation control requirements. The overall layout of the site is shown in Figure 1.

A combined seepage-cutoff system was adopted for the retaining structure, including cement-soil mixing wall reinforcement, diaphragm wall, and ultra-high-pressure jet grouting. The diaphragm wall has a depth of 78.5 m and is embedded into moderately weathered argillaceous silty sandstone. The vertical supporting system was constructed using the top-down method. The system consists of one reinforced concrete crown beam, three circular ring beams, and eighteen lining structures. At the bottom of the excavation, anchor piles were installed, and a layered reinforced concrete base slab was cast to seal the pit bottom. This structural system was designed to ensure sufficient global stiffness and anti-uplift stability of the ultra-deep foundation pit. The schematic cross-section of the foundation pit is shown in Figure 2.

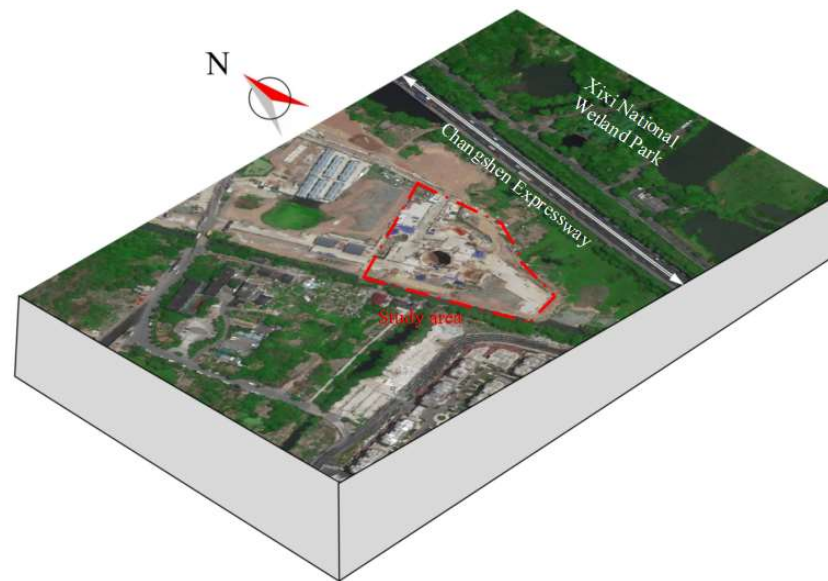


Figure 1. Study area overview.

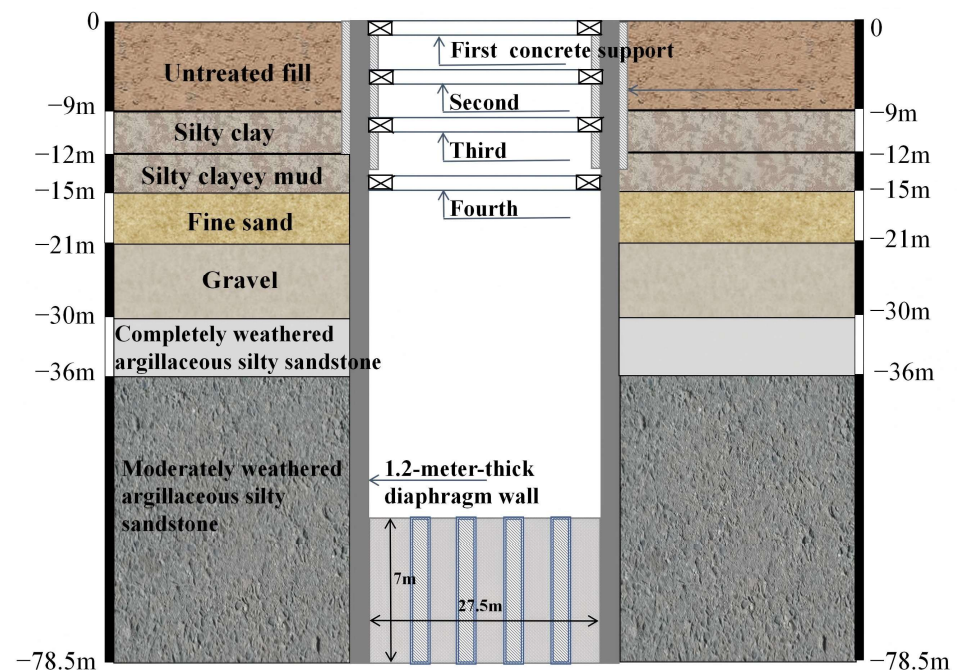


Figure 2. Schematic diagram of the foundation pit Section.

2.2. Finite Element Method

2.2.1. Construction of the Finite Element Model

Considering the coupled effects of dewatering, recharge, and diaphragm wall–soil interaction, a three-dimensional finite element model of the foundation pit excavation was established using ABAQUS(2023). The dimensions of the computational domain were approximately 500 m in length, 500 m in width, and 120 m in height, and the foundation pit was located at the center of the model. The excavation depth was about 71.5 m, and the circular pit had a diameter of 27.5 m. The diaphragm wall thickness was set to 1.2 m, and the wall depth was 78.5 m, with an embedded depth of approximately 7 m. The model was discretized using hexahedral solid elements. A total of 227,416 elements were generated in the whole model. Mesh refinement was applied in the excavation region and within the influence zone of the foundation pit to achieve a balance between computational

accuracy and efficiency. To reduce the complexity of parameter input, soil layers with similar mechanical properties were merged and simplified into seven strata. A schematic diagram of the numerical model is shown in Figure 3.

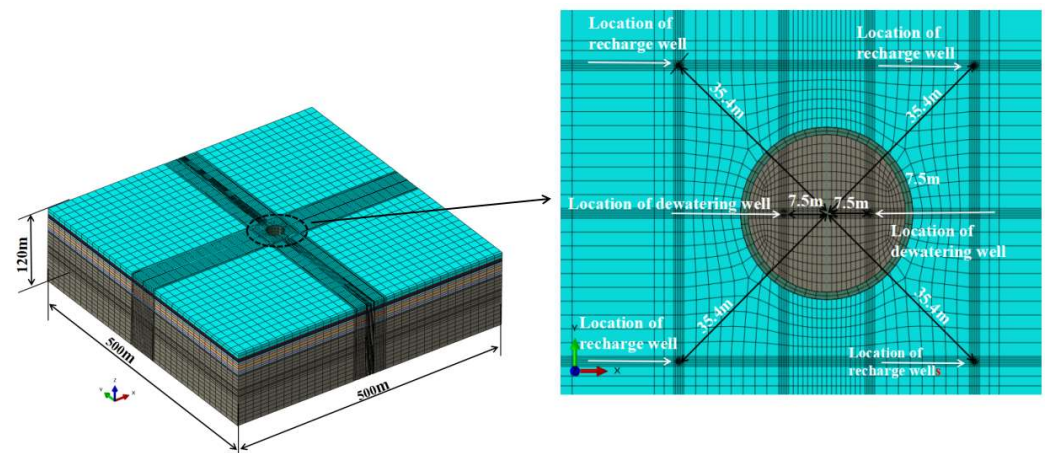


Figure 3. Numerical calculation model of the foundation pit.

To ensure consistency between the numerical simulation process and the field construction procedure, staged calculation conditions were established according to the actual excavation and support construction sequence. The foundation pit was constructed using the top-down method, and the excavation process was divided into six main stages. Each stage included soil excavation and the construction of supports or linings. The monitoring data used for model validation were selected after the completion of the corresponding construction stage, when the stress state of the supporting structure had become relatively stable. This ensured that the simulated conditions were comparable with the actual field conditions. Table 1 presents the construction schedule.

Table 1. Construction schedule.

Construction Stage	Excavation Depth/m	Main Construction Activities	Actual Groundwater Control Measure	Corresponding Field Monitoring Data
Stage 1	Excavation to −7.0 m	Excavation to −7.0 m; installation of 1.4 m × 1.0 m concrete struts at the top of the pit and 1.2 m × 1.0 m concrete struts at −6.5 m	Dewatering was adopted to control the groundwater level inside the pit	Monitoring data of ground surface settlement and diaphragm wall lateral displacement were collected after completion of this stage to reflect the deformation response after shallow excavation and initial support installation
Stage 2	Excavation to −17.0 m	Excavation to −17.0 m; installation of 1.4 m × 1.0 m concrete struts at −9.5 m	Continuous dewatering was conducted to maintain a safe groundwater level below the excavation surface	Monitoring data collected after this stage were used to reflect deformation development after deeper excavation and second-level support installation
Stage 3	Excavation to −28.0 m	Excavation to −28.0 m; installation of 1.4 m × 1.0 m concrete struts at −14.5 m	Continuous dewatering was conducted to control confined groundwater and seepage effects	Monitoring data collected after this stage were used to evaluate ground settlement and wall displacement during the intermediate excavation stage

Table 1. Cont.

Construction Stage	Excavation Depth/m	Main Construction Activities	Actual Groundwater Control Measure	Corresponding Field Monitoring Data
Stage 4	Excavation to −41.0 m	Excavation to −41.0 m; lining construction proceeded with excavation	Continuous dewatering was maintained together with the support system to control deformation	Monitoring data collected after this stage were used to reflect deformation response during deep excavation and progressive lining construction
Stage 5	Excavation to −54.0 m	Excavation to −54.0 m; lining construction proceeded with excavation	Continuous dewatering was maintained to control the influence of deep groundwater	Monitoring data collected after this stage were used to reflect ground and retaining-structure deformation during ultra-deep excavation
Stage 6	Excavation to −71.5 m, reaching the final excavation depth of the shaft	Excavation to −71.5 m; construction of anchor piles and casting of the base slab	Dewatering was maintained until base slab closure and structural stabilization	Monitoring data collected after final excavation and base slab construction were used for model validation against ground settlement and diaphragm wall deformation

2.2.2. Constitutive Model and Boundary Conditions

In the present foundation pit model, the soil behavior was described using the porous elastic model together with the Modified Cam-Clay model. The model parameters were determined based on field sampling and laboratory tests. To reduce the influence of sample variability on the parameter selection, statistical analysis was conducted on multiple groups of test results, and representative average values were adopted as the input parameters for the model. Meanwhile, the parameters were calibrated using the field monitoring data of ground surface settlement and diaphragm wall displacement. This improved the rationality of the parameter selection and the reliability of the numerical simulation results. The key parameters are listed in Table 2.

Table 2. Soil layer parameters for the model.

Soil/Structure	Depth (m)	Unit Weighty (kN/m ³)	Void Ratio <i>e</i>	Horizontal Permeability Coefficient <i>K_H</i> (cm/s)	Vertical Permeability Coefficient <i>K_v</i> (cm/s)	Logarithm of Elastic <i>K</i> /(Pa)	Logarithm of Plastic Volumetric Modulus <i>λ</i>
① Untreated fill	0~9	18.9	0.915	6×10^{-7}	5×10^{-7}	0.03	0.35
② Silty clay	9~12	19.2	0.806	8.3×10^{-7}	7.5×10^{-7}	0.022	0.27
③ Silty clayey mud	12~15	17.6	1.156	4×10^{-7}	3×10^{-7}	0.095	0.65
④ Fine sand	15~21	19.4	0.636	2×10^{-3}	1.5×10^{-3}	0.008	0.45
⑤ Gravel	21~30	22	0.35	4.5×10^{-2}	4×10^{-2}	0.004	0.02
⑥ Completely weathered argillaceous silty sandstone	30~36	20.5	0.597	9×10^{-6}	8.5×10^{-6}	0.008	0.05
⑦ Moderately weathered argillaceous silty sandstone	36~120	25	0.35	6×10^{-6}	5×10^{-6}	0.004	0.02
Diaphragm Wall	78.5	25	-	-	-	3.15×10^{10}	-
concrete support	-	25	-	-	-	3.15×10^{10}	-
Dewatering Well	71.5	25	-	-	-	3.15×10^{10}	-

The computational domain was set as 500 m × 500 m × 120 m, with the foundation pit located at the center of the model. This range is much larger than the influence zone of foundation pit excavation and dewatering, which can effectively reduce the influence of artificial boundaries on the pore pressure field and deformation field. A drainage

boundary with a pore pressure of 0 was applied at the top of the model. Horizontal displacement constraints were imposed on the lateral boundaries, and both horizontal and vertical displacements were constrained at the bottom boundary. A constant-head boundary was adopted for the far-field groundwater boundary to reflect the recharge effect of the surrounding hydrogeological environment. The dewatering wells and recharge wells were simulated using prescribed flow-rate boundaries. Similar treatment methods have also been adopted in recent numerical studies on deep foundation pit dewatering and recharge [6,11]. The hydraulic boundary settings of the wells were defined to be consistent with the boundaries of the corresponding aquifers, so that the continuity of the seepage field and the consistency of boundary conditions could be ensured.

3. Results

3.1. Finite Element Simulation Results and Model Validation

To verify the reliability of the established finite element model, the measured deformation during the excavation under actual construction conditions was compared with the numerical results. A monitoring section including ground surface settlement and diaphragm wall deformation was selected to obtain the transverse deformation profile, as shown in Figure 4.

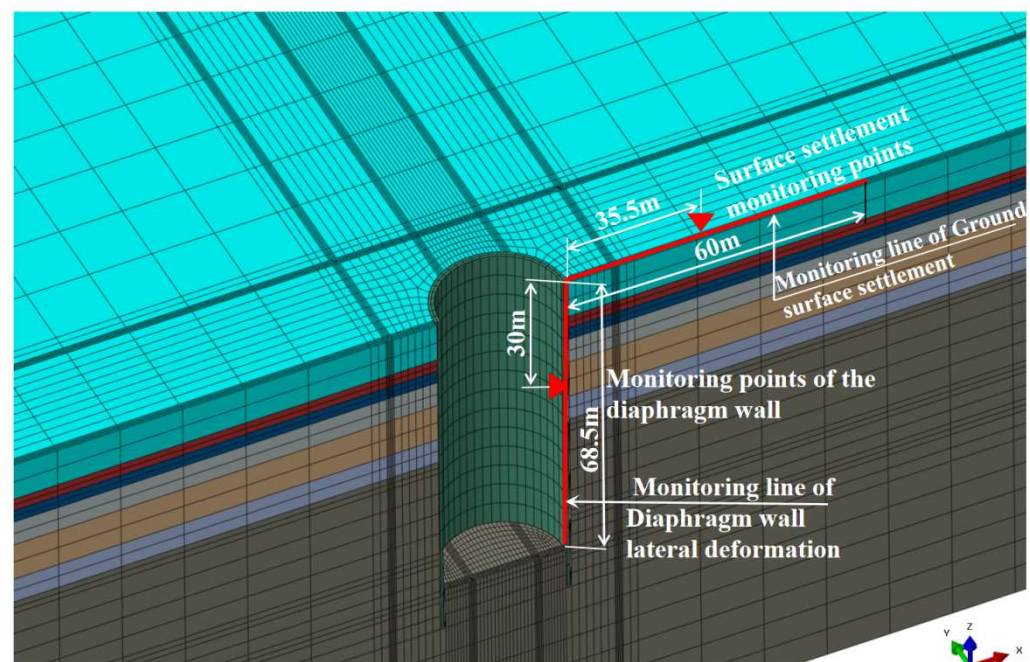


Figure 4. Schematic diagram of ground surface and diaphragm wall monitoring section.

The comparison between measured and simulated ground settlement is presented in Figure 5. Both the measured curve and the numerical results exhibit a typical “settlement trough” distribution. The settlement first increases and then decreases with increasing distance from the pit, which is consistent with the general deformation pattern induced by deep excavation in soft soil areas. The numerical simulation captures the location of the main settlement trough reasonably well, and the maximum settlement occurs at a distance of approximately 35.5 m from the pit edge. This discrepancy was not caused by a single factor, but by the combined effects of soil parameter variability, fluctuations in groundwater boundary conditions, idealization of the construction process, and field monitoring errors. The arrangement of monitoring points and local construction disturbances may also have contributed to the deviations. The superposition of these factors resulted in relatively large

differences between the simulated and measured values at some local monitoring points, with a maximum discrepancy of approximately 21.45%.

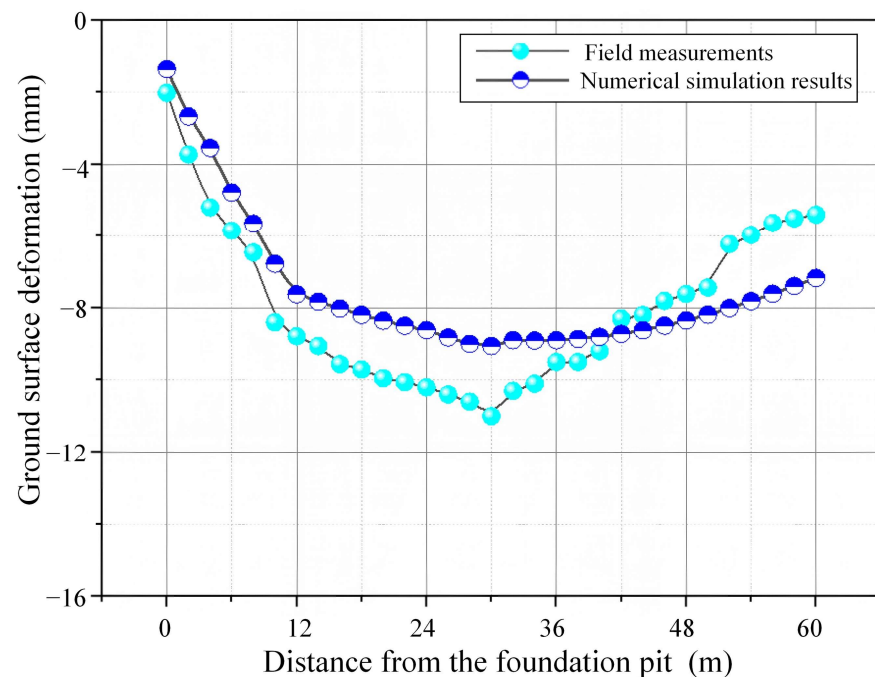


Figure 5. Comparison of measured and simulated ground surface deformation.

Figure 6 presents a comparison between the measured and simulated lateral displacements of the diaphragm wall. The differences between the measured and simulated values may mainly be attributed to the simplification of the wall–soil contact conditions, the equivalent treatment of support stiffness, and deviations between the simulated and actual working conditions. The comparison with field monitoring data further verifies the reliability of the proposed numerical model.

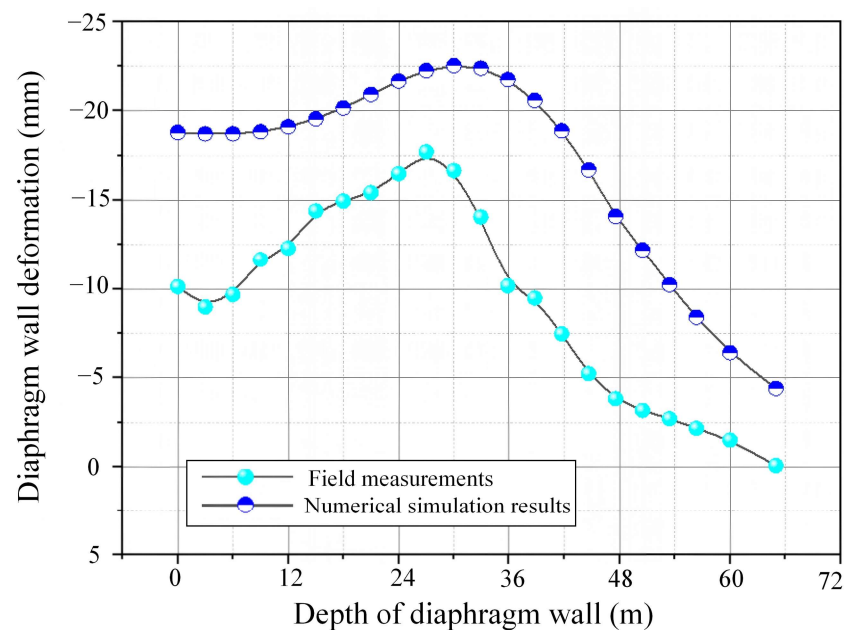


Figure 6. Comparison of measured and simulated diaphragm wall deformation.

Figure 7 shows the variation of ground surface displacement at characteristic points with excavation time. The numerical simulation results exhibit a stepwise increase in

settlement corresponding to the six excavation stages. This stepwise pattern reflects the immediate response of the soil to staged excavation and support installation. Meanwhile, the curve also presents the cumulative settlement deformation measured in the field. During the final excavation stage, the settlement gradually tends to stabilize, indicating that the numerical model can reasonably reflect the time-dependent evolution of ground surface settlement and accurately reproduce the staged response of the soil during excavation.

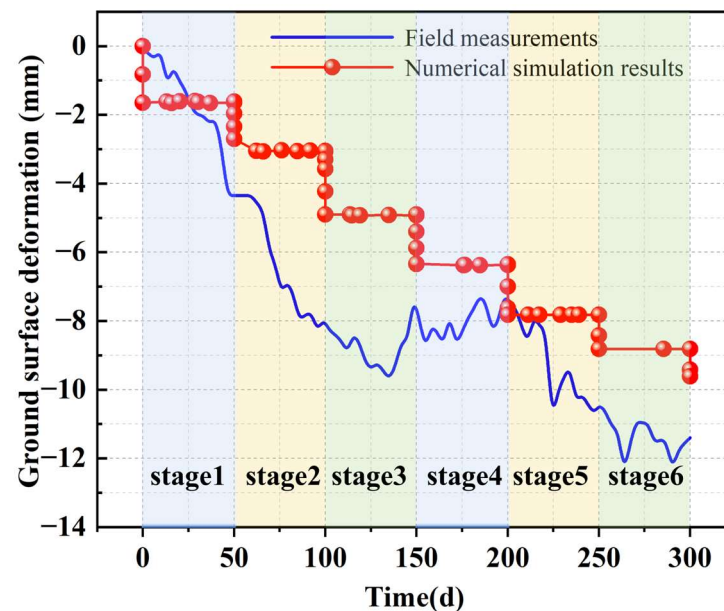


Figure 7. Ground surface settlement at characteristic points over excavation time.

For both ground surface deformation and the lateral deformation of the diaphragm wall, although certain discrepancies exist at some local positions, the simulation results can reasonably capture the shape of the ground surface settlement trough, the location of the maximum settlement, the deformation pattern of the diaphragm wall, and the overall variation trend. Moreover, the simulated and measured values are of the same order of magnitude, which demonstrates the rationality of the model and is consistent with the findings of Wang et al. (2022) [21]. Therefore, the model can be used to analyze the deformation characteristics of the foundation pit and the main influencing mechanisms.

3.2. Change of Diaphragm Wall and Ground Surface Deformation

To analyze the influence of dewatering rate on the deformation of the circular foundation pit, the point located at the center of the monitoring section in Figure 4 was selected for analysis. As shown in Figure 8, without considering the recharge effect, both the ground surface settlement and the lateral displacement of the diaphragm wall at the characteristic point increase with increasing pumping rate. When the dewatering rate increases from 0.4 m/h to 0.8 m/h, the ground settlement increases from −14.03 mm to −15.23 mm, while the lateral displacement of the wall increases from −20.47 mm to −22.05 mm. This indicates that the increase in dewatering rate intensifies the deformation response of the surrounding soil and the retaining structure around the foundation pit.

Under the condition without recharge, different dewatering rates (0.4 m/h, 0.6 m/h, and 0.8 m/h) lead to different pore water pressure distributions. As shown in Figure 9, dewatering induces a clear drawdown funnel around the pumping wells in the foundation pit, and the seepage field around the pit changes significantly as the dewatering rate increases. When the dewatering rate is 0.4 m/h, the drawdown funnel forms gradually and shows a relatively gentle shape. When the rate increases to 0.6 m/h, the funnel becomes

more pronounced. This indicates that a higher dewatering rate causes a stronger variation of the seepage field in the zone centered on the pumping wells.

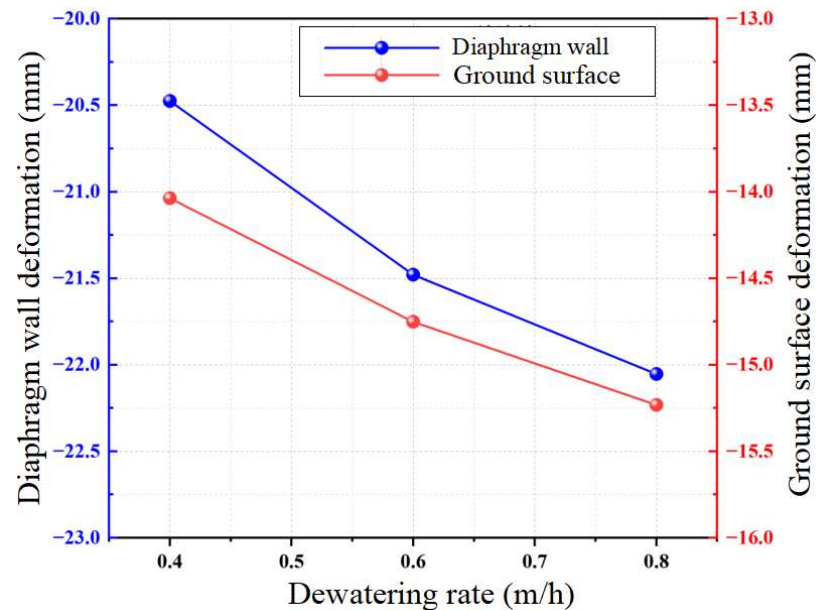


Figure 8. Deformation of ground surface and diaphragm wall under different dewatering rates.

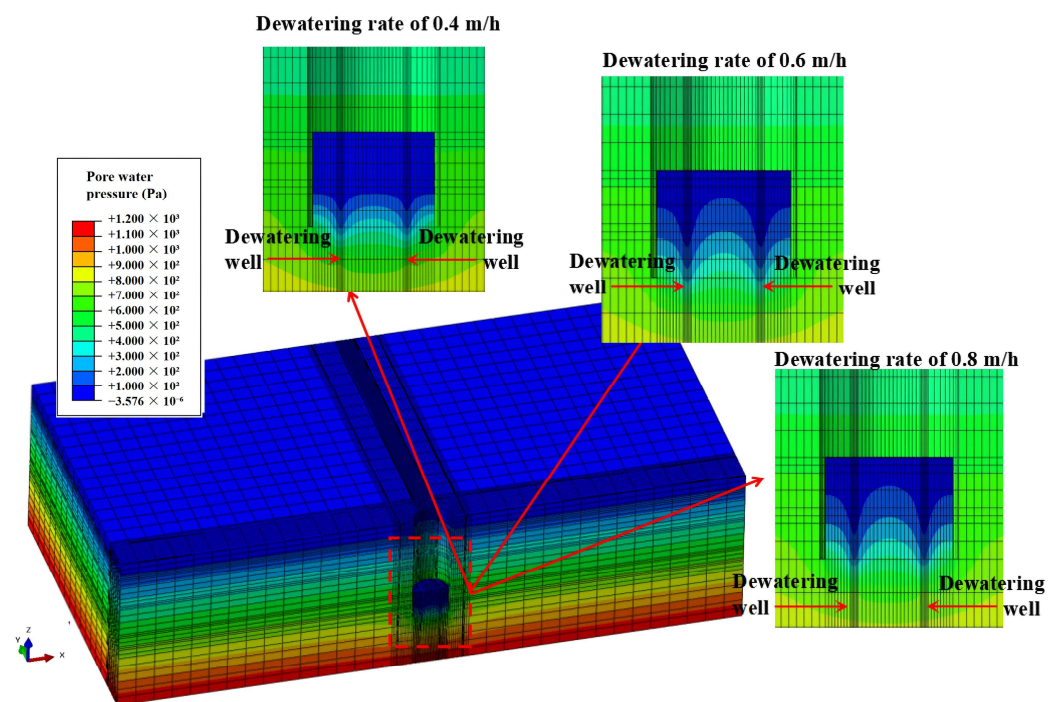


Figure 9. Pore water pressure contours under different dewatering rates.

As shown in Figure 10, the effective stress around the pumping wells increases due to dewatering, indicating that the dissipation of pore water pressure leads to a significant increase in soil effective stress. With increasing dewatering rate, the increase in horizontal effective stress changes the distribution of active earth pressure acting on the diaphragm wall, further intensifying the lateral squeezing deformation of the wall. This deformation becomes more pronounced as the dewatering rate increases.

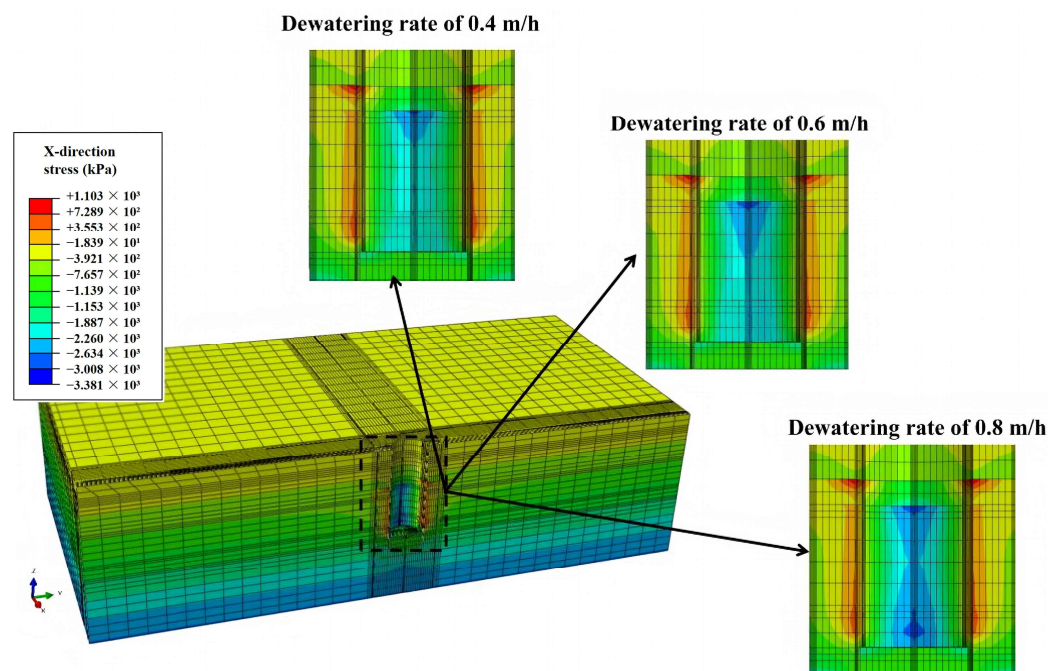


Figure 10. X-direction stress contours of the foundation pit under different dewatering rates.

3.3. Change of Ground Surface and Diaphragm Wall Deformation Under Different Recharge Rates

To analyze the influence of recharge on the deformation and seepage field, the pumping rate was fixed at 0.4 m/h, and the effects of different recharge rates (0.4, 0.6, and 0.8 m/h) on ground surface deformation and diaphragm wall deformation were investigated. As shown in Figure 11, the ground settlement gradually decreases with increasing recharge rate. When the recharge rate is 0.4 m/h, the ground deformation is -18.75 mm, while it decreases to -7.75 mm when the recharge rate increases to 0.8 m/h. This indicates that the increase in recharge rate effectively reduces ground surface deformation.

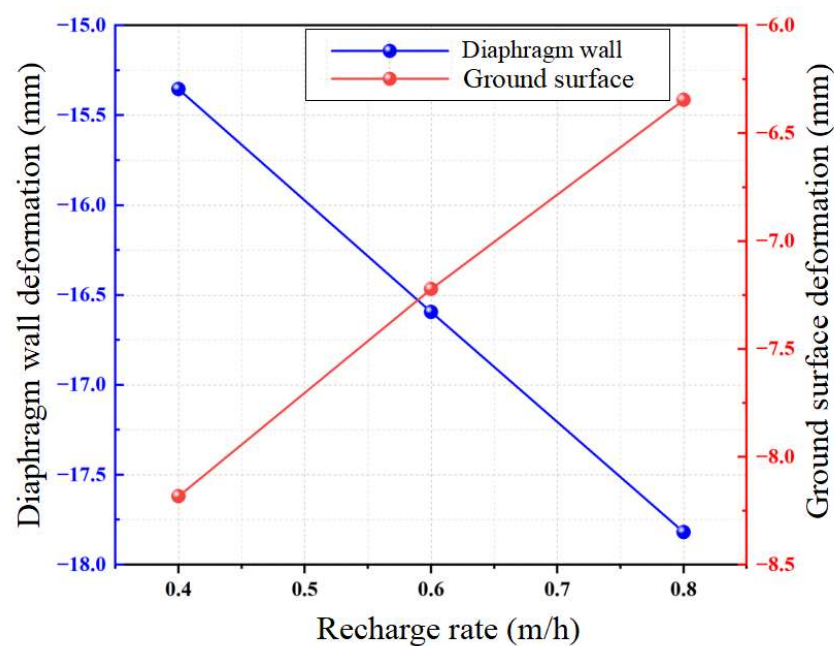


Figure 11. Deformations of the ground surface and diaphragm wall induced by different recharge rates.

Different from the ground response, the lateral displacement of the diaphragm wall shows an increasing trend with increasing recharge rate. When the recharge rate increases from 0.4 m/h to 0.8 m/h, the lateral displacement changes from -15.35 mm to -17.81 mm. This phenomenon occurs because recharge compensates for the groundwater level decline caused by dewatering. A higher recharge rate enlarges the saturated zone and elevates pore water pressure, possibly causing buoyancy-induced ground heave. The increased soil unit weight alters wall loads and increases lateral displacement of the diaphragm wall.

To investigate the influence of recharge parameters on the deformation and seepage fields, the pore water pressure distribution under different recharge rates was compared with a fixed dewatering rate of 0.4 m/h (Figure 12). As shown in Figure 12, recharge increases the pore water pressure around the recharge wells in the foundation pit, gradually saturating the soil. With increasing recharge rate, the saturated soil zone also expands.

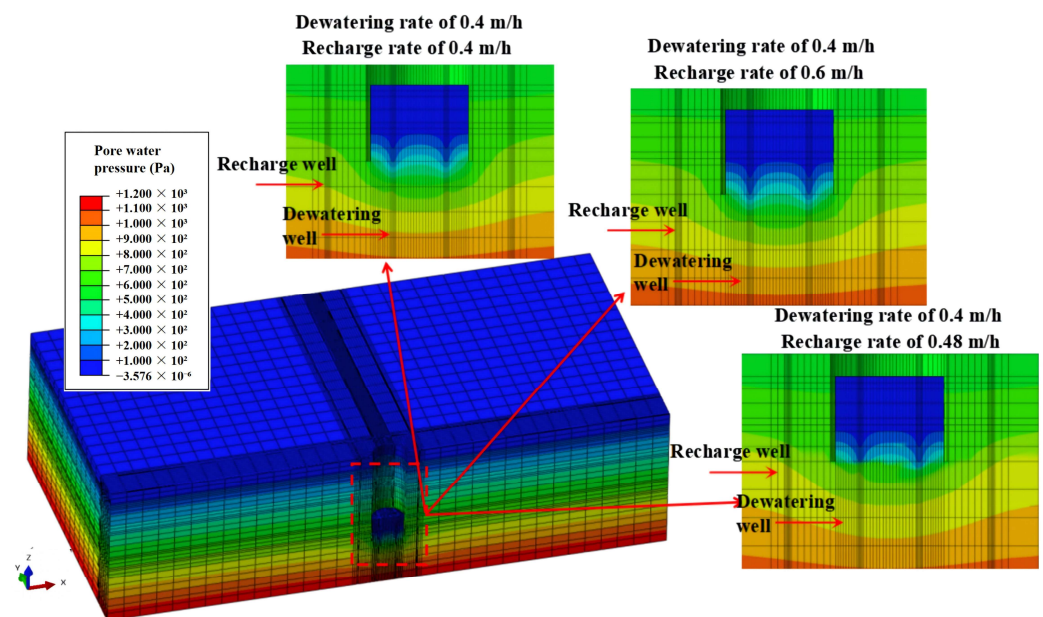


Figure 12. Pore water pressure contours under different recharge rates.

The variation of the seepage field directly induces a redistribution of the effective stress in the soil. As shown in Figure 13, under the condition of a fixed dewatering rate of 0.4 m/h, the regulatory effect of recharge on the soil effective stress gradually emerges with the increase in the recharge rate from 0.4 m/h to 0.8 m/h, indicating that the recovery of pore water pressure caused by recharge can offset the increase in effective stress induced by dewatering to a certain extent. With the increase in the recharge rate, the stress concentration zone caused by dewatering is restrained, and the magnitude of stress increase is slowed down. Under recharge conditions, pore pressure recovery reduces the increase in effective stress outside the foundation pit, thereby limiting soil consolidation and reducing ground surface settlement. However, this effect does not necessarily lead to a reduction in diaphragm wall displacement, because the increase in pore water pressure and the expansion of the saturated zone may increase the lateral hydro-soil pressure acting on the wall. As the recharge rate increases, the mitigation of ground surface settlement becomes more pronounced, whereas the lateral displacement of the diaphragm wall may increase.

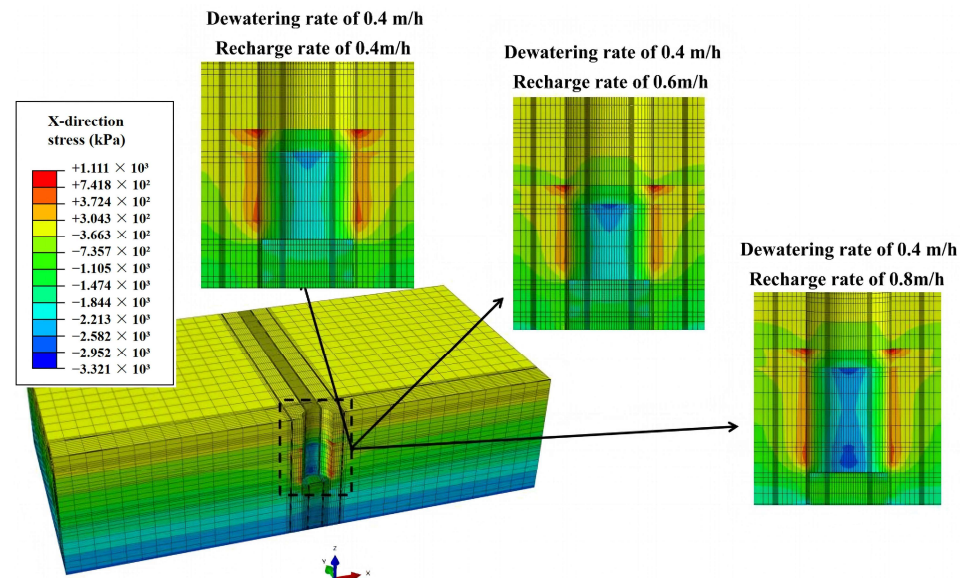


Figure 13. X-direction stress contours of the foundation pit under different dewatering and recharge rates.

4. Discussion

4.1. Mechanism of Circular Foundation Pit Deformation Induced by Dewatering

It is indicated by numerical simulations that dewatering not only alters the distribution of the site's seepage field but also significantly affects the stress and deformation fields around the foundation pit. Regarding the evolution of the seepage field, as the pumping rate is increased from 0.4 m/h to 0.8 m/h, the pore water pressure at the dewatering wells is gradually reduced, forming a drawdown funnel. The drawdown funnel becomes more pronounced as the dewatering rate increases. The reduction in pore water pressure results in an increase in soil effective stress, which in turn induces deformation of the foundation pit.

With increasing dewatering rate, both ground settlement and lateral displacement of the diaphragm wall are observed to increase. This occurs because the dissipation of pore water pressure directly causes an increase in effective stress within the soil pores, triggering pit deformation. Higher pumping rates expand the zone of increased soil stress, causing soil compression and lateral displacement under effective stress, thereby intensifying the overall deformation of the soil surrounding the foundation pit.

4.2. Mechanism of Circular Foundation Pit Deformation Induced by Recharge

The numerical simulation results show that groundwater recharge not only changes the distribution of the seepage field around the foundation pit, but also significantly affects the stress field and deformation field of the soil. Specifically, when the recharge rate increases from 0.4 m/h to 0.8 m/h, the pore water pressure around the recharge wells gradually increases, and the local saturated zone expands. These changes further have different effects on ground surface settlement and diaphragm wall deformation. In terms of ground surface deformation, recharge can compensate for the loss of pore water pressure induced by dewatering and thereby partially alleviate the consolidation compression effect caused by dewatering. Therefore, as the recharge rate increases, ground surface settlement gradually decreases, and a certain tendency toward ground heave may occur.

From the perspective of effective stress path evolution, dewatering and recharge affect soil deformation through different mechanisms. The lateral displacement of the diaphragm wall does not necessarily decrease as ground surface settlement decreases. Recharge

increases the pore water pressure behind the wall, thereby changing the effective stress path of the soil behind the wall and the interaction between the wall and the surrounding soil. On the one hand, pore pressure recovery reduces the effective stress of the soil. On the other hand, the development of local high-pore-pressure zones and the expansion of the saturated zone increase the lateral hydro-soil pressure acting on the wall. When the recharge rate is relatively high, the horizontal displacement of the diaphragm wall may further increase. Therefore, recharge has a dual effect on foundation pit deformation. It can reduce ground surface settlement induced by dewatering; however, an excessively high recharge rate may increase the risk of lateral deformation of the retaining structure.

4.3. Future Study

This study indicates that dewatering tends to exacerbate ground surface deformation, whereas groundwater recharge can effectively mitigate ground surface settlement. When important buildings or sensitive facilities are located near the foundation pit, protective measures should be implemented. Reducing the dewatering rate can help limit ground deformation, but it may prolong the construction schedule. In contrast, a properly designed recharge scheme can restore pore water pressure and reduce ground surface settlement, while avoiding excessive increases in diaphragm wall displacement. Therefore, the design of dewatering and recharge schemes should not only focus on groundwater level recovery or the minimization of ground surface settlement, but also consider the deformation control requirements of the diaphragm wall and surrounding structures. Future studies could further investigate optimal dewatering–recharge strategies by integrating numerical simulation with field monitoring. This includes exploring reasonable ranges of dewatering and recharge rates, the timing of recharge initiation, and appropriate control measures, with the aim of minimizing ground surface settlement and support structure displacement while ensuring construction safety and controllable structural deformation.

It should be noted that this study still has certain limitations. First, during the actual field construction of this project, only dewatering measures were implemented, and on-site groundwater recharge was not conducted. Therefore, the field monitoring data cannot be directly used to validate the time-lag relationship between recharge initiation and the stabilization of ground heave. In this study, the recharge condition was set as an extended simulation scenario after the model had been validated under the field dewatering condition. It was mainly used to analyze the mechanisms by which recharge affects ground surface settlement and diaphragm wall deformation. For the conditions of this project, a lag effect may exist between pore water pressure recovery and the ground surface deformation response after recharge initiation, which could affect the accuracy of settlement or heave predictions. Second, this study adopted a continuum-based finite element method, which is capable of simulating pore water pressure transmission, changes in effective stress, and soil deformation responses during dewatering. However, it is difficult for this approach to directly capture mesoscopic processes such as local leakage, fine-particle migration, or seepage-induced failure that may occur in cohesive soil layers under high hydraulic gradients. Although the numerical model has been validated against field monitoring data and can reasonably capture the overall deformation behavior of the foundation pit, the initial parameters of the Modified Cam-Clay model in this study were primarily determined based on geotechnical investigation reports, laboratory test results, and relevant numerical studies, particularly referring to the numerical simulation study by Xu et al. (2024) [11] on recharge in deep foundation pits. A systematic sensitivity analysis of the Modified Cam-Clay model parameters has not yet been conducted.

Future studies could focus on ultra-deep foundation pit projects where recharge measures are actually implemented. By combining continuous monitoring data of recharge

flow rate, ground surface settlement, and diaphragm wall displacement, the time-lag relationship between recharge initiation and the stabilization of ground heave can be further investigated. Numerical models with different element types and mesh sizes will also be established for comparative analysis. For example, the model could be re-meshed using tetrahedral solid elements and compared with the currently adopted hexahedral element model, with particular attention to key results such as ground surface settlement and diaphragm wall displacement. By comparing their performance in terms of computational accuracy, convergence behavior, and efficiency, the influence of element type on the hydro-mechanical coupling response of ultra-deep circular foundation pits can be further evaluated. At the same time, the discrete element method could be employed to investigate the effects of particle migration, pore structure evolution, and seepage-induced failure under high hydraulic gradients on foundation pit deformation. It should also be noted that future studies could further extract the effective stress paths of representative soil elements behind the diaphragm wall. By combining these paths with the time-history variations in pore water pressure, horizontal effective stress, and lateral wall displacement, the coupling mechanism between pore pressure recovery and diaphragm wall deformation under groundwater recharge can be quantitatively analyzed. Finally, the effects of key parameters, such as the compression index and swelling index, on ground surface settlement, pore water pressure variations, and diaphragm wall deformation should also be carefully evaluated. This will further enhance the reliability and applicability of the proposed coupled seepage–deformation model for similar ultra-deep foundation pit projects.

5. Conclusions

An ultra-deep circular foundation pit in Hangzhou was investigated using a three-dimensional finite element model incorporating coupled dewatering and recharge effects. Diaphragm wall deformation during excavation was analyzed to support deformation prediction and risk management under complex conditions. The main findings are summarized as follows:

- (1) A three-dimensional finite element model considering both dewatering and recharge was established. Its reliability was verified by comparing simulated ground settlement and diaphragm wall deformation with field measurements, showing good agreement in magnitude and variation trends.
- (2) With increasing dewatering rate, pore water pressure at the dewatering wells gradually decreased, forming a drawdown funnel. The drawdown funnel became more pronounced at higher pumping rates, and the reduction in pore water pressure increased soil effective stress, expanded the high-stress zone, and induced soil compression and lateral displacement, thereby intensifying overall pit deformation. Both ground settlement and lateral displacement of the diaphragm wall were observed to increase accordingly.
- (3) Recharge gradually increased pore water pressure around the wells, forming localized high-pressure zones. This produced two contrasting effects: ground surface deformation was gradually reduced as buoyancy induced by the expansion of the saturated soil zone caused ground heave, with the heave becoming more pronounced at higher recharge rates. Conversely, lateral displacement of the diaphragm wall increased because infiltration of recharge water elevated pore water pressure and expanded the saturated soil zone, generating additional lateral thrust on the wall. Together, these mechanisms amplified overall soil deformation around the pit.

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