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Numerical simulation study on settlement of surrounding soil caused by sink construction in soft ground layer

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Abstract:

Sink construction can easily trigger surrounding surface settlement, which poses a hidden danger to road surfaces and buildings, and measures need to be taken to reduce settlement. In this study, the sink operation of the Nanniwan Power Tunnel Project was combined with numerical simulation and actual monitoring to study the impact of reinforcement treatment on surface settlement and conduct model feasibility analysis. The results show that the surface settlement can be effectively controlled after rotary spray pile reinforcement, and it is more obvious with the increase in construction depth; the maximum settlement value is reduced by 40.2% after the first section is sunk, and 61.8% after all of them are sunk. The soil settlement after reinforcement shows a spoon-shaped change with the distance, and the in-situ soil shows a parabolic shape change. The settlement monitoring value of each point was greater than the theoretical value; the maximum was 5.3 mm, 43.2% higher than the theoretical value, and the minimum was 7.1 mm, 9.2% higher than the theoretical value, which is within the permissible range of construction.

Keywords: sink; surface settlement; numerical modelling; reinforcement treatment

1 INTRODUCTION

As a common deep foundation construction method in foundation engineering, sinkhole construction is widely used in bridge construction and urban underground engineering[1]. Sinkholes penetrate deep into the soil layer through the process of self-weight and settlement, and the force characteristics of the sidewall earth pressure and lateral friction resistance directly affect the stability of the sinkhole, the construction efficiency and the final quality of the project. Therefore, it is very important to study the mechanical characteristics of sinkhole sinking.

In the research field of sinkhole construction, there have been a large number of theoretical analysis and experimental research[2]. The traditional research mainly focuses on the characteristics of soil pressure distribution on the side wall during sinking of sinkhole, especially the analysis of shear strength of soil body, friction coefficient, and the reaction force of soil body on the side wall of sinkhole[6]. These studies provide a more explicit preliminary understanding and calculation method of sidewall earth pressure during sinkhole sinking[7]. With the deepening of engineering practice, researchers have gradually realized that in the actual sinkhole construction, the change of lateral friction resistance is not only related to factors such as the type, denseness and humidity of the soil, but also closely related to the morphology of the sinkhole, the speed of construction and the sinking method[8]. Some studies have shown that the distribution of lateral friction resistance during sinkhole sinking shows complex non-uniformity, and there is even a localized phenomenon of friction resistance agglomeration, which has an important impact on the smooth sinking of sinkhole and the stability assessment during the construction process[9].

The existing studies also have certain shortcomings[10]. Most of the studies still have limitations in the simulation and testing process. Many studies focus on a single soil layer or a simplified soil model, ignoring the effects of different soil layers and soil quality changes on lateral friction resistance[11]. During sinkhole sinking, the complex interactions at the soil-sinkhole interface show diversity in different construction environments, and it is often difficult for existing computational models and theoretical analyses to comprehensively take into account the multiple variables in the actual construction process[13]. Although a large amount of theoretical research and experimental data have been accumulated, relatively little monitoring data are available for actual projects, especially in the complex underground environment, and the lack of monitoring data on lateral friction resistance of sinkholes has led to a lack of understanding of the mechanics to the sinkhole construction process.

In summary, it is of great significance to study the distribution characteristics of lateral friction resistance during sinkhole sinking, especially the changes in the distribution of friction resistance under complex soil conditions, in order to accurately predict the forces during sinkhole construction, optimize the construction scheme, and improve the safety of sinkhole construction. This study aims to explore the distribution law of lateral friction resistance and its change characteristics during sinking of sinkhole through the combination of on-site monitoring data and theoretical analysis, so as to provide theoretical basis and technical support for the subsequent engineering design and construction.

2 PROJECT OVERVIEW

2.1 Engineering environment

The periphery of the proposed working well area is mainly surrounded by city roads, demolition sites, and existing houses, with relatively dense buildings and a high mobility of vehicles and personnel. The topography of the area is generally flat, and the landform of the site belongs to the first-grade alluvial terrace of the Yangtze River. The top soil layer is an artificial fill, downward in the order of soft clay, sand layer, and bedrock, and the engineering properties of the upper soil are poor. According to the design scheme, the inner diameter of the Sink was 12.5m, the wall thickness was 1m, and the sinking depth was 12.15m. 0.5m of the outer wall of the sink was reinforced using rotary piles with a reinforcement range of 1m. The Sink was 10m deep, and it adopted a three-section layered sinking program, whereby the next layer of the sink was fabricated and sank after sinking the current layer to the designed depth. The sink and support structures of the rotary piles are shown in Figure 1.

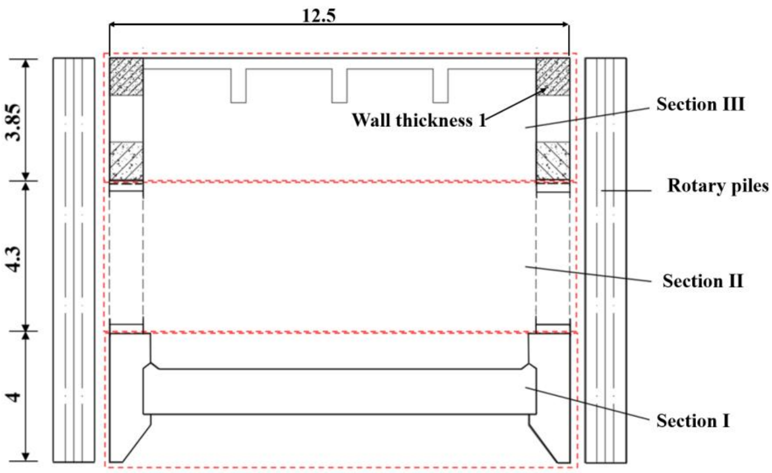


Figure 1 Diagram of Sink and support structure (in metre)

2.2 Geological condition

According to the detailed investigation report and indoor geotechnical test in the early stage of the project, the mechanical parameters of each stratum of this Sink construction are as follows Table 1. To facilitate the modelling analysis, the depth of the stratum was only considered as the theoretical effective influence range, which was taken as 30 m. From the surface to the depth of the stratum, the layers were miscellaneous fill, plain fill, silty clay, clay, and silt sand sandy clay, which are referred to in the subsequent numerical simulation.

Table 1 Stratigraphic parameters

stratum (geology)	(of a speech etc) profundity /m	density /kg-m^{-3}	Poisson's ratio	modulus of elasticity /MPa	cohesion /kPa	angle of internal friction /°
miscellaneous fillings	2	1650	0.2	9.5	8	8
stockpile soil	3	1700	0.2	10.0	10	8
silty clay	7	1720	0.3	13.0	16	8
clays	6	1800	0.3	13.5	23	12
silt sand sandwiched between clays	12	1810	0.3	15.0	12	19

2.3 Record of subsidence observations

The sinking of the well from the first section to the completion of the sinking of the whole experienced a total of approximately 43 days, of which the 6th–27th and 31st–40th days to meet the height of the work, the actual sinking time of a total of 11 days. During sinking, four elevation observation points were arranged at 90° intervals in a circular direction on the outside of the well body to monitor sinking attitude. The variation curves of the sinking depth and maximum elevation difference with respect to the actual sinking time are shown in Figure 2. The sinking speed was very slow on days 6th and 9th day, which was presumed to be due to the need to reinforce the bottom of the pit during the fabrication of the new section of the sink; thus, the sinking speed was slowed down at the early stage of sinking owing to the need to break the reinforcement layer first, and then the sinking speed was restored to a stable level after the reinforcement layer was completely removed.

Similarly, the maximum height difference remained almost unchanged on Days 6 and 9. Because of the sinking scheme combining excavator digging and boom fetching, it was difficult to ensure uniform excavation, and the well body was prone to deflection, resulting in large fluctuations in the height difference during the pre-sinking period. With an increase in the joint height and sinking depth, the height difference fluctuation gradually decreased owing to the gradual increase in the lateral earth pressure on the well structure, and finally stabilized within a reasonable range.

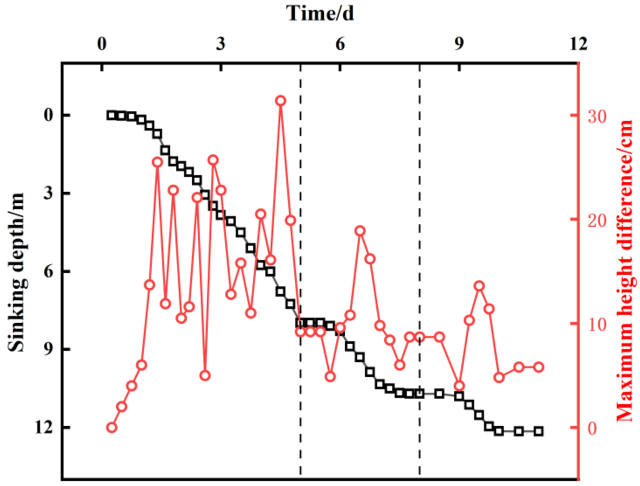


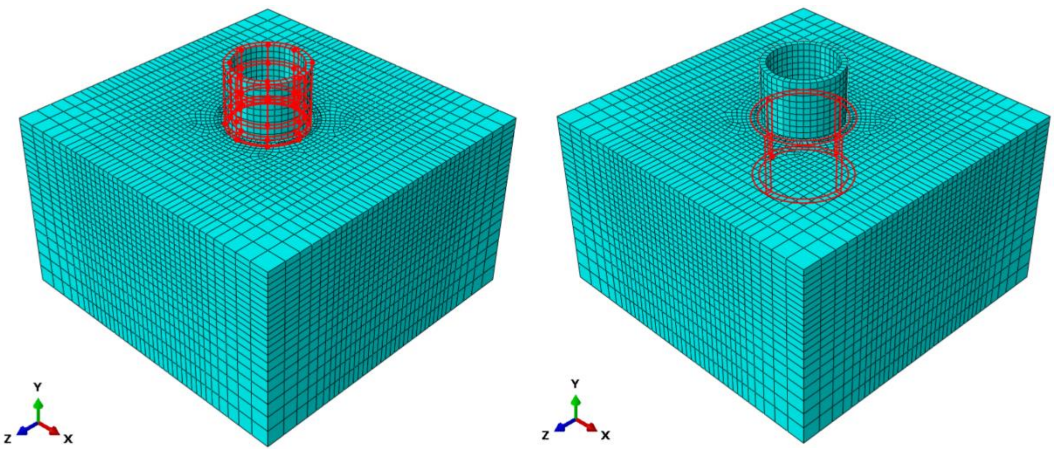
Figure 2 Variation curve of sinking depth and maximum height difference

3 NUMERICAL SIMULATION PROGRAMME

3.1 Modelling

The numerical model was established using the finite element analysis software ABAQUS, considering the complexity of the environment around the sink. To facilitate the calculation and analysis, the model needs to be targeted to simplify the treatment. Assuming that the soil was uniformly distributed along the horizontal direction, the Mohr-Coulomb ideal elastic-plastic constitutive model was adopted. Sink and rotary piles are modelled by an elastic principal model, and rotary piles are generated by the birth-death unit method and activated in the piling process; thus, the disturbance of the soil body by pile generation and pit bottom reinforcement is not considered.

Taking full consideration of the scope of influence of sink construction, the size of the soil body model was set to 50m×50m×30m. The dimensions of the sink and rotary piles are as described in the previous section. The well body parts are divided into three sections during creation, and the next section is generated after the previous section has sunk into the soil body to fit the actual construction in sections. To consider the calculation speed and accuracy, the mesh division of the soil body gradually becomes denser from the boundary to the center, with a total of 47,872 nodes and 43,155 cells. In the assembly stage, all the rotary piles and the bottom of the sink were placed into the soil body, which was convenient for establishing the contact relationship between the two and the soil body in time. The positions of the two in the assembly body are highlighted in red in Figure 3.



(a) Sinks (b) Spinning piles

Figure 3 Numerical model for Sink construction

3.2 Restrictive condition

In this simulation, the moving loads of pedestrians and vehicles in the construction periphery as well as the fixed loads of pipe joints and material stacking were not considered, and the normal phase constraints on the four sides of the soil body and the three-directional constraints on the bottom surface were set in the initial analysis step. Before excavation, the soil body was balanced for ground stress using the automatic balancing method to achieve a stress state close to the actual one.

To improve the computational efficiency, fixed constraints in the horizontal direction (X, Z direction) were applied to the rotary piles generated after removing the soil body in the pile addition section for the entire process. Meanwhile, to simulate the support effect of the sinking section by section on the lateral soil body, horizontal direction fixed constraints were applied to the sidewalls of the soil body removed in each step of the sink excavation and sinking process, and the constraints were cancelled when the next part of the soil body was excavated until the sinking was completed.

3.3 Analysis step

Since this simulation compares and analyses the surface settlement effect of Sinks in the original soil and reinforced soil, the simulation is divided into two main parts: the original soil is subjected to geo stress equilibrium, i.e. the generation of Sinks and excavation and sinking of Sinks, as a control group; the reinforced soil is subjected to geo stress equilibrium, and then the sinking of Sinks is carried out, as an experimental group.

To improve the accuracy and avoid the convergence problem of the model caused by too large a depth of a single excavation, the soil excavation was carried out ten times. In addition to the first layer of the soil body in the sink generation stage, nine sinking analysis steps were generated, and the displacement control method was adopted to achieve sinking of the sink. Taking the experimental group as an example, the detailed analysis step settings are presented in Table 2.

Table 2 Experimental group analysis step settings

simulation step	Working condition setting
1	Initial Geo Stress Equilibrium
2	Generate Spinning Piles
3	Generating Sinks
4	First excavation sinking
5	Second excavation and sinking
...	...
12	Ninth excavation and sinking
13	fulfil

Note: The control group is not set up for step 2, and there are 12 analysis steps in total.

4 ANALYSIS OF RESULTS

4.1 Theoretical Settlement Comparison

To study the actual effect of the reinforcement treatment on the surface settlement around the sink, first, the settlement at different distances around the sink was obtained through the simulation results, which intuitively reflects the difference between the two under ideal conditions. After completing the simulation, the field output variable "displacement" and U2 direction (vertical) were obtained, and the results are shown in Figure 4. The vertical deformation diagram is shown in Figure 4.

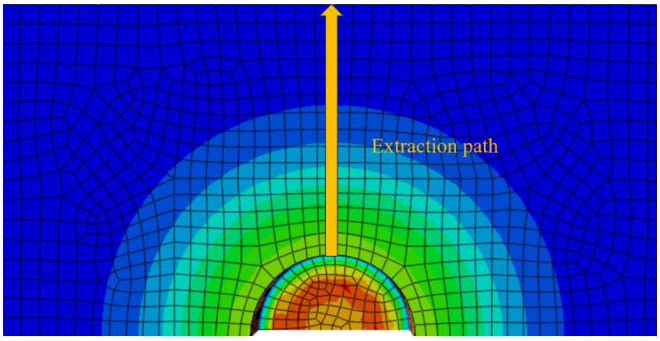
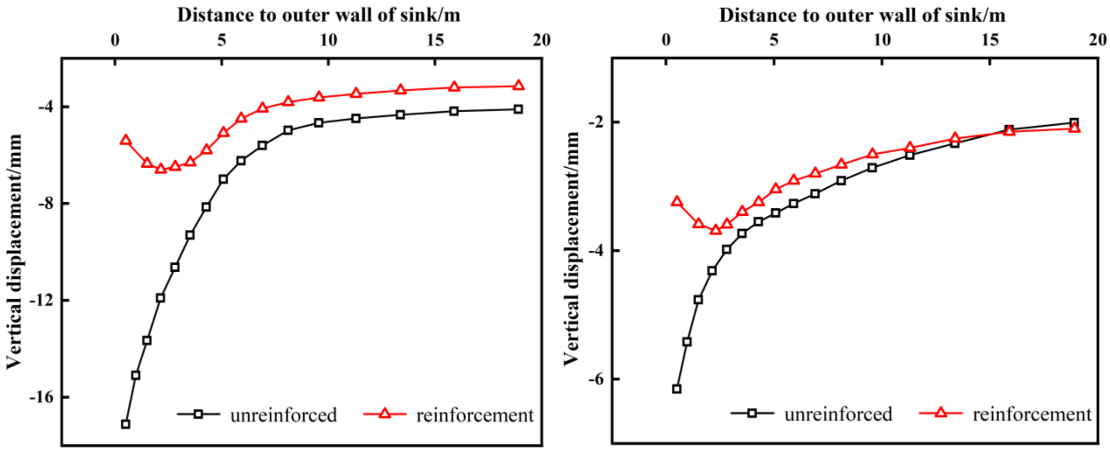


Figure 4 Soil vertical deformation profile

The settlement of the ground surface under different simulated construction phases can be obtained by creating a path of nodes on the soil surface pointing vertically along the outside of the sink towards the edge of the soil and extracting the data. The surface settlement at the end of the first section of the sink and at the end of the entire sink are presented in the form of vertical displacements, as shown in Figure 5.



(a) Completion of sinking of the first section (b) Completion of overall sinking

Figure 5 Comparison of surface settlement in different simulation stages

Under the same simulation conditions, the surface settlement after sinking the first section of the sink and the entire sink had the same trend in distance: the surface settlement away from the outer wall of the sink decreased gradually, and the rate of settlement decrease decreased with an increase in distance. The main difference between the two is that the surface settlement of the unreinforced soil body still increases when it is close to the outer wall of the sink, and the rate of increase also increases gradually. The overall shape of the settlement curve is parabolic, and the maximum settlement point is the well - soil contact. For the reinforced stratum, the maximum settlement point was located at a certain distance outside the wall, and the surface settlement trend from this point to the edge was similar to that of the unreinforced stratum, whereas the settlement trend from the inner to the outer wall was the opposite, with a gradual decrease in the amount of settlement, and the curve was in the shape of a spoon.

After the completion of the first section sinking, the minimum surface settlement value without reinforcement is 2.01 mm and the maximum is 6.17 mm; after reinforcement, the minimum surface settlement value is 2.09 mm and the maximum is 3.69 mm. The maximum settlement after reinforcement is located at 2.3m of the outer wall, and the settlement value without reinforcement at the same distance is 4.18 mm. The maximum settlement value after reinforcement is reduced by 40.2%, and the minimum settlement value increases by 4%, while the maximum settlement value reduces by 11.7% compared with the same distance. by 11.7%, whereas the minimum settlement value increased by 4%. The minimum settlement increased by 4% (a show that near the outer wall, the settlement of the reinforced surface and the overall settlement of the peripheral (computing) smaller comparison of the unreinforced case, which proves that the supporting effect of the rotary piles has a certain effect on the reduction of the surface settlement.

Unlike the monotonicity of the settlement change without reinforcement, the settlement after reinforcement gradually decreased near the outer wall. The main reason for this is that rotary piles of a certain thickness were set up on the outer side of the sink when the model was created. With regard to the mechanical properties, the piles of the concrete structure are significantly larger than the various soil bodies in terms of density and modulus of elasticity and form the effect of the retaining wall after being placed into the soil body. As the Sink is continuously excavated downwards, the self-gravitational stress of the original soil body is unloaded, the soil body at the bottom produces rebound, there is a tendency for the lateral soil body to enter into the well[12], and the soil in the lateral direction has a tendency to inflow into the well. However, the existence of rotary piles significantly limits the lateral displacement of the soil body, and the soil body tends to move towards the rotary piles gathered downward from the bottom of the pit into the pit, upward to produce a certain accumulation, in a small range of mitigation of the original settlement effect.

It is worth noting that after a certain distance away from the outer wall, the surface settlement of the reinforced soil is slightly higher than that of the unreinforced soil, a result that is mainly due to the fact that the rotary piles in this numerical simulation were applied using in-situ generation. In this analysis step, the entire soil body occupying the pile location was directly removed using deactivation, and the pre-positioned rotary piles were activated. After the removal of the soil, similar to the main body of the sink, the soil around the rotary piles experienced some degree of settlement and horizontal displacement towards the pile location, but the depth of the pile generated in one pass was greater than that of the single excavation of the sink, resulting in a more pronounced settlement effect. On this basis, the displacement of the peripheral soil caused by the excavation and sinking of the subsequent sink is gradually presented by the pile body obstruction, and becomes increasingly obvious with the approach to the outer wall. Thus, the amount of surface settlement at the distal end is only in the first section of the sinking of the initial construction has not yet reflected the effect of reinforcement, but the trend of the overall settlement of the periphery as well as the amount of settlement under the near and medium distances clearly reflects the good effect of the reinforcement.

After all Sinks are sunk, the surface settlement value without reinforcement is minimum 4.12 mm and maximum 17.13 mm; the surface settlement value after reinforcement is minimum 3.16 mm and maximum 6.61 mm, and at this time, the location of the maximum settlement point after reinforcement moves inward to the outer wall at 2.16m. To visually compare the settlement of the sink after sinking and the effect of the reinforcement, the starting point of the extraction path of the model was set to A0, the end point was A1, and the maximum settlement point after reinforcement was B. The increase in settlement under the two conditions is listed in Table 3, and the changes in settlement and overall maximum value of each point in the two stages under the reinforced condition are listed in Table 4.

Table 3 Increase in settlement at the end of each condition

Working condition	A0	B	A1 (minimum settlement value)
unreinforced	177.6 per cent	175.2 per cent	104.9 per cent
reinforcement	67.3 per cent	79.1%	51.2 per cent

Table 4 Comparison of settlement values after various stages of reinforcement

point	A0	B	A1 (minimum settlement value)	Maximum settlement value
sinking of the first section	-47.5 per cent	-11.7 per cent	4 per cent	-40.2 per cent
Overall sinking	-68.3 per cent	-42.5 per cent	-23.3 per cent	-61.8 per cent

As can be observed from the data displayed in table above, the role of rotary spray piles in controlling the settlement of the periphery was gradually highlighted during the process of sink excavation and sinking. After finishing all the sinking work, the increase in the settlement value of each location after reinforcement was significantly reduced compared with the non-reinforced condition, and the decrease in the settlement value of each location was also significantly improved compared with that after the first section of sinking.

With the fabrication of the sunken wells and excavation construction, the weight of the well body and depth into the soil continued to increase, and the strata in contact with it, while providing upward frictional resistance, were also subjected to downward reaction forces from the sunken wells and subsided. The cumulative settlement of the multiple strata ultimately acted on the ground surface, resulting in the settlement of the ground surface. The presence of the rotary spray piles limits the lateral displacement of the soil into the wells, and some of the soil produces a small amount of stacking effect close to the piles, but the excavation to the depth of the soil also increases the range of the soil affected and the displacement of the soil, and more of the soil is hindered by the piles from moving inward but is still squeezed inward by the rest of the soil, resulting in a strengthening of the stacking effect manifested in the difference between A0 and B and the inward movement of B-point. Move.

It should be noted that there are limits to the soil retaining effects of rotary piles. When the excavation is shallow, soil movement is limited by the pile. However, when the excavation is deeper, the limited depth of the pile body cannot prevent the movement of the deep soil to the well; at this time, the soil body produces an obvious settlement at the same time, which will also drive the pile body to a certain settlement.

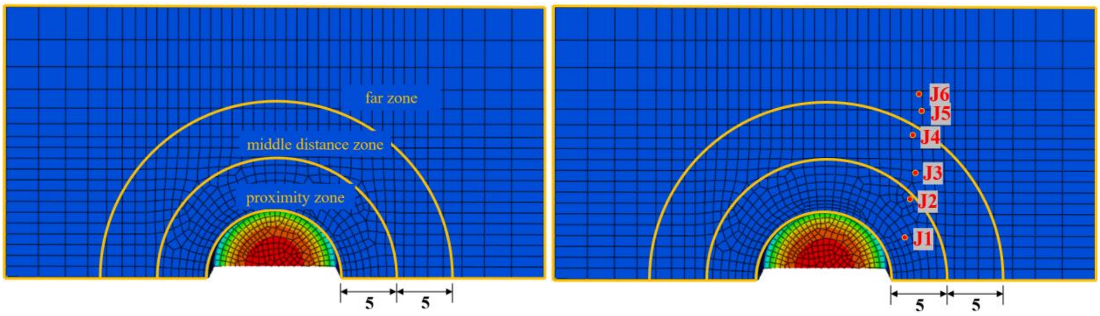
4.2 Comparison of settlement monitoring

The settlement results obtained through numerical simulation theoretically show that the surface settlement after reinforcement treatment can be effectively controlled, but the construction and solution of the model will ignore part of the actual situation, making the results differ from the monitoring data. Therefore, it is necessary to combine the two for analysis. From the preset monitoring points around the sink, six points with certain intervals were selected for comparison, and the distance between each point and the outer wall of the sink is shown in Table 5.

Table 5 Distance between the observation point and the outer wall of the Sink

observation point	Distance from outer wall/m
J1	2.5
J2	4.8
J3	6.6
J4	9
J5	11.1
J6	12.4

Simultaneously, considering that surface settlement is affected by distance, the area around the settlement is divided into three study areas, namely, the near-range, middle-range, and far-range areas, according to the interval of 5m and 10m from the outer wall, and there are two monitoring points in each area. The division of the area and location of the monitoring points are shown in Figure 6.



(a) Delineation of the study area (b) Location of monitoring points

Figure 6 Monitoring environment setup (in metres)

The monitoring and modelling results for each monitoring point were plotted and compared. The monitoring data were recorded from the beginning of the first node sinking to the completion of construction. Because the position of each node in the numerical model is fixed, it is not possible to arbitrarily select a point at a specific distance; therefore, the model node for comparison with each monitoring point is the nearest point of the two. Considering the simulation results, reinforcement was selected to balance the initial settlement of the soil; therefore, the simulation was performed from the completion of the rotary pile generation process to the completion of the calculation.

Proximity Zone: The modelled settlement value of monitoring point J1 is 6.5 mm and the actual monitoring value is 7.1 mm, which is 9.2% higher than the modelled value; the modelled settlement value of monitoring point J2 is 5.6 mm and the actual monitoring value is 6.3 mm, which is 12.5% higher than the modelled value. The change curve of settlement in this area is shown in Figure 7.

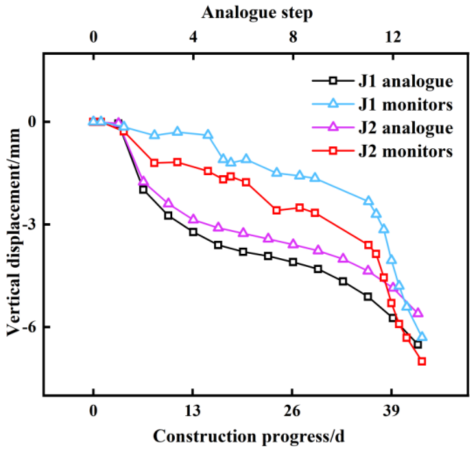


Figure 7 Comparison of settlement in the proximity zone

Under the simulated conditions, the settlement velocity of the two monitoring points shows that it increases first, then decreases, and is smooth, and finally increases. Under the actual condition, both settlement velocities are smooth in the first and middle stages, with occasional small rebound, until the late stage of construction when it increases significantly. Under the simulated conditions, the application of rotary spray piles caused settlement of the surrounding soil, and the nearest monitoring points J1 and J2 showed an obvious performance. The piles then acted as soil retainers in the subsequent excavation and sinking, moderating the trend of surface subsidence. As mentioned earlier, when the depth of the sink is close to the burial depth of the piles, a large amount of lateral soil is influent into the well; therefore, the settlement of the soil will accelerate at the later stage of the simulation. The actual working conditions are more complicated and susceptible to environmental and human interference, such as the movement and stacking of large equipment and the coming and going of neighboring vehicles, so there are fluctuations in the monitoring data. In fact, the slurry was driven into the soil through the grouting pipe and mixed with it to form a rotary spray pile, which was stronger than the cylinder directly generated in the simulation, and the effect of limiting the soil displacement and settlement was more obvious.

Medium Distance Zone: The simulated value of settlement at monitoring point J3 is 4.3 mm and the actual monitored value is 5.5 mm, which is 27.9% higher than the simulated value; the simulated value of settlement at monitoring point J4 is 3.7 mm and the actual monitored value is 5.3 mm, which is 43.2% higher than the simulated value. The change curve of settlement in this area is shown in Figure 8.

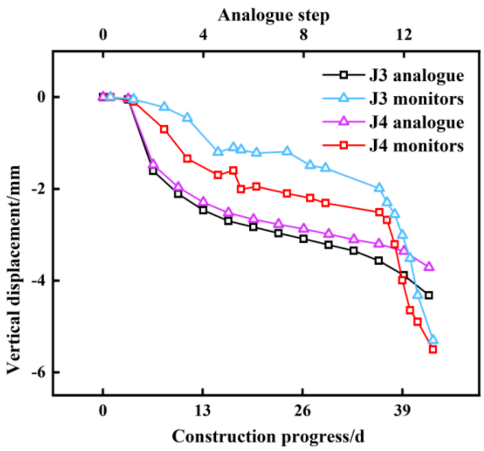


Figure 8 Comparison of Settlement in the Middle Distance Zone

Compared with the near-distance zone, the difference between monitoring points J3 and J4 in the middle-distance zone is reduced in both the modelled and monitored values of subsidence, which, to some extent, proves the variation in subsidence with distance, as described in the previous section. However, the error between the measured and simulated values of each of the two monitoring points in the area is larger than that in the close-range zone, proving that the actual settlement trend is still different from theory.

In terms of the surface settlement rate at the later stage of the monitoring points, the monitored values were significantly larger than the modelled values, and this result was more significant than that of the proximity zone. Theoretically, the trend of surface settlement in the middle distance zone is more moderate than that in the near distance zone; therefore, the results of the settlement monitoring in this area are more affected by the disturbance of the actual construction environment.

Distant Zone: The simulated value of settlement at monitoring point J5 is 3.5 mm and the actual monitored value is 4.4 mm, which is 25.7% higher than the simulated value; the simulated value of settlement at monitoring point J6 is 3.4 mm and the actual monitored value is 4 mm, which is 17.6% higher than the simulated value. The change curve of settlement in this area is shown in Figure 9.

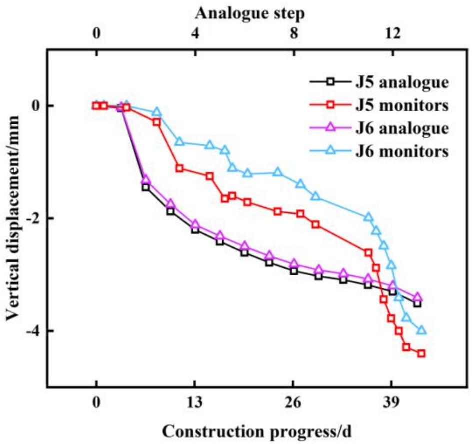


Figure 9 Comparison of settlement in the remote zone

The difference between the simulation and monitoring in the remote area is smaller than that in the middle-range area, but still larger than that in the near-range area. The settlement in this zone is more moderate and stable from the simulation, and has met the safety needs in the actual project. Compared with the first two zones, the later monitoring curves also showed a sudden increase in settlement, but it was controlled at the end.

As mentioned above, some conditions are simplified and ignored in the numerical simulation to balance the computational difficulty and the actual working conditions. As a matter of fact, the location of the Sink is a road surface, except for the rotary piles, the surrounding ground surface has been hardened to a certain extent, so that the actual monitoring value of the settlement has been smaller than the simulated value in the first and middle periods. At the same time, in the summer rainy period, there is a certain amount of water table in the construction stratum, and the increasing depth of subsidence will gradually produce the surge of water and sand from the surrounding soil to the well, which is an important factor leading to the obvious subsidence of the ground surface, whereas the stratum in the simulation does not have any water table, so the results remain stable and greater than the monitoring results for most of the time, until the later stages of the construction when there is unavoidable surge of water etc., which exacerbated the actual subsidence of the ground surface.

Comparison of the settlement in the three study areas shows that there are differences between the surface settlement in the actual project and the ideal model, and it is impossible to restore the precise direction of the modelling law due to the influence factors of many aspects of reality, but the construction model based on a specific stratum can still provide predictions for the construction plan. In this paper, the monitoring curves and simulation curves are different in terms of numerical values, but the overall trend is similar, and the simulated and monitored settlement values of each monitoring point are within the actual permissible range, which proves that the theoretical surface settlement after reinforcement treatment is more in line with the actual situation, and also reflects the reasonableness of the model.

5 CONCLUSION

The variation of the surface settlement value with distance obtained by finite element analysis shows that the unreinforced stratum is parabolic, with the settlement value increasing from the edge to the outer wall of the Sink and the increase of the settlement becoming larger; the reinforced stratum is spoon-shaped, with the maximum settlement location at a certain distance from the outer wall, and the settlement value decreasing gradually from the maximum settlement point to the outer wall and the edge.

The maximum surface settlement value of the reinforced stratum was reduced by 40.2% after the first section was sunk and 61.8% after all the sections were sunk compared to the unreinforced stratum, indicating that the rotary spray piles played a role in limiting the soil displacement during the sinking of the Sink.

The final monitoring values obtained from the six settlement monitoring points set around the Sink are all larger than the theoretical values, with the largest one located at 9m from the outer wall, with a monitoring value of 5.3mm, 43.2% higher than the theoretical value; and the smallest one located at 2.5m from the outer wall, with a monitoring value of 7.1mm, 9.2% higher than the theoretical value.

The settlement monitoring values were less than the theoretical values during the pre-construction and mid-construction phases due to the hardening of the ground. In the later stage, due to the influence of precipitation and groundwater level, the actual monitoring value is larger than the theoretical value. The similarity of the two trends indicates that the surface settlement can be effectively controlled after the hardening treatment.

DATA SHARING AGREEMENT

The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

DECLARATION OF CONFLICTING INTERESTS

The authors declared no potential conflicts of interest with respect to the research, author-ship, and publication of this article.

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