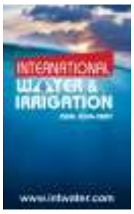


International Water and Irrigation
Volume 44 Issue 1 (2025)
ISSN: 0334-5807
Pages 283- 292

Field Monitoring and Numerical Simulation Research on Earth Pressure of Sink Construction in Soft Ground Layer

Tao Deng[1]*, Shangchun Liu[1], Ailin Huang[1],Xinhua Jiang[1],Zhihu Xiang[1],Kan Huang[1]

[1]Central &Southern China Municipal Engineering Design and Research Institute Co,Ltd, Hubei,Wuhan, China

Corresponding Author's Email:303757554@qq.com

Abstract Through the on-site monitoring method, the change of soil pressure in the sinking process of circular sink of pipe jacking project is analysed and studied, and combined with the finite element numerical simulation method, the distribution pattern of soil pressure is compared and analysed. The results show that: with the increase of sinking depth, the shape of earth pressure curve at each point along the height of the sink gradually changes from a spoon shape to a bimodal shape, and the maximum point of earth pressure is located at a certain height from the foot of the blade; the earth pressure on one point of the outer wall of the sink increases with the increase of depth, and the comparative analysis at specific depths shows that the simulated values and the monitored values are more consistent, and the two are between the active earth pressure and the static earth pressure, gradually approaching to the active earth pressure with the increase of depth. Gradually close to the active earth pressure.

Keywords: pipe jacking; working well; circular sink; soil reaction; displacement.

1. Introduction

As the working well which provides recoil reaction force for pipe jacking, in the past, due to the short jacking distance, small pipe diameter and shallow burial, the jacking force required for jacking was small, coupled with the high strength of the working well itself and its good structural properties, the working performance of the working well can generally meet the requirements. However, with the increase of jacking distance, pipe diameter and burial depth, the jacking force required for pipe jacking is getting bigger and bigger, which has risen from 100 tonnes to 1,000 tonnes in the past, and the safety of the working wells can no longer be ignored[1] . The soil of the back wall behind the working well provides the jacking counter force to the pipe jacking, when the jacking force is too large and the soil stability is not enough, it will lead to various engineering problems.

At present, there are fewer studies at home and abroad on pipe jacking work wells, circular work wells vertical soil resistance, usually considered rigid work wells vertical.

The direction of linear change[2-3] , flexible working well vertical direction to form a smooth curve, jacking pipe at the back seat of the soil reaction force is larger, the two ends of the smaller, some scholars believe that the simulated normal distribution[4-6] , the calculation of the approximation that the trapezoidal distribution.

The horizontal earth resistance distribution of circular working well is more complicated, Feng Haining et al.[7] In the calculation of shaped sink, it is considered that the increment of back earth resistance caused by top force reaction is distributed on the semicircle according to the centripetal cosine curve; Song Weining et al[2] considered that the distribution of earth resistance in the horizontal plane is semi-elliptical; Wei Zang et al[5] .assumed that the circular sinkhole working well produces the overall displacement, and used the method of calculating the earth pressure considering the displacement to calculate the annular earth resistance of recumbent wall. However, the existing researches are seriously lack of field measurement data verification.

International Water and Irrigation
Volume 44 Issue 1 (2025)
ISSN: 0334-5807
Pages 283- 292

2. Objectives

This study relies on the Nanniwan Power Tunnel Project, and the selected study sink is the starting shaft for pipe jacking, the location of which is shown in Figure 1. The structure is made of C35 concrete with impermeability class P8 and reinforced steel structure conforming to Q235B grade in cast-in-place operation, with an outer diameter of 12.5m, wall thickness of 1m except for 1.2m at the foot of the cutting edge, and the height of the shaft is about 13m.

The structure construction is divided into four sections, of which the lower first section is the edge foot layer, the edge foot is 1m high, the height of this section is 3.2m; the second section is the pipe jacking hole layer, the height is 3.8m; the third and the fourth layers are the conventional layer as well as the retaining wall layer above, the height is 6m. the fabrication of the subsections are all carried out after the previous section is poured and conserved, the sinking well structure is shown. Sinking was carried out twice, respectively after the first and second sections and the third and fourth sections were made. The sinkhole and its surrounding reinforcement structure are shown in Figure 2.

The sinkhole was sunk in two times after the casting of the sub-section construction was completed. The first sinking started after the completion of the first and second sections, and the sinking was carried out until the top of the second section was slightly higher than the surrounding ground, with a depth of about 6.8m; the second sinking was carried out after the completion of the third section and the retaining wall, and the sinking was carried out until the top of the retaining wall was slightly higher than the ground, with a depth of about 12.8m.

Figure. 1 Location of sink

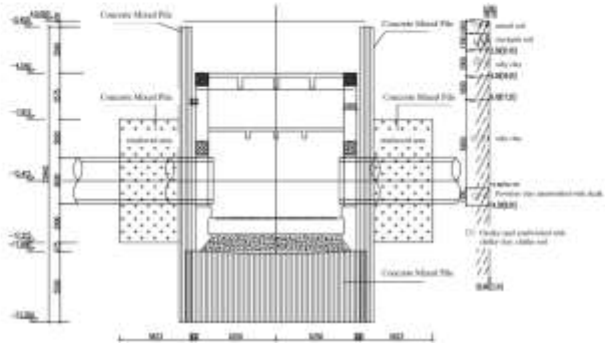
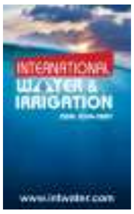


Figure. 2 Structure of the immersed shaft

According to the detailed investigation report and indoor Geo technical test in the early stage of the project, the mechanical parameters of each stratum of this sink construction are as follows Table 1. From the surface to the depth, they are miscellaneous fill, plain fill, powdery clay, clay and silt sand with clay in order.

Table 1 Strati graphic 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



International Water and Irrigation
Volume 44 Issue 1 (2025)
ISSN: 0334-5807
Pages 283- 292

3. Site monitoring and analysis of results

3.1 Monitoring programme

This field test combines the site-specific construction situation, mainly focuses on soil pressure monitoring, by arranging multiple soil pressure gauges at different locations and different heights, real-time monitoring of the soil pressure at different heights and different locations of the caisson, and researching the caisson stress at different points and different depths through the time change and location change, so as to reflect the stability of the caisson structure.

A total of four monitoring sections were set up for the test, of which I-1 and II-1 were the main monitoring levels with heights of 3.2m and 7m, respectively, and I-2 and II-2 were the auxiliary monitoring levels with heights of 1.8m and 5.2m, respectively, as shown in Figs. 3~5. When designing the programme, the sensors on each level are basically distributed in a pentagonal shape, with all the sensors placed in five point directions. In practice, according to the changes in the form of steel reinforcement and form work erection in the construction process, the location of the specific sensors to make appropriate offset adjustments.

Due to the different functions and usage requirements of each sensor, there are differences in the placement locations. The difference in azimuth angle between the sensors at each point on the site is relatively small, and it is considered that the difference in azimuth can be ignored in the calculation. The realisation of the basic function of the earth pressure gauge requires it to be in direct contact with the ground layer, so it is arranged in the outermost layer; the circumferential arrangement of the reinforcement gauge is chosen to be on the reinforcement bar against the interior, while the circumferential arrangement is chosen to be as close as possible to the circumferential reinforcement gauge; and the inclinometer is arranged vertically on the reinforcing bar close to the outer form work.

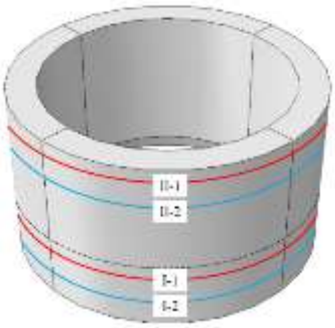


Figure. 3 Map of monitoring section locations

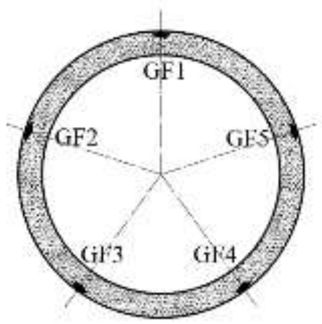
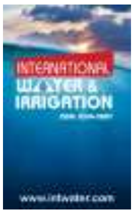


Figure. 4 Distribution of sensor points in layer I

Figure. 5 Distribution of Sensor Points in Layer II

3.2 Analysis of results

An example of layer I soil pressure gauge is analysed. The change of monitoring data during the first sinking is shown in Figure 6. As can be seen from the figure, the earth pressure on the outer wall of the sinkhole increases with the increase of the depth of the soil, and the growth trend is fluctuating. With the sinking construction, the earth pressure gauge monitoring



International Water and Irrigation
Volume 44 Issue 1 (2025)
ISSN: 0334-5807
Pages 283- 292

data appeared frequent fluctuations, as can be seen in the figure, the occurrence of large fluctuations in the time node, the sinkhole appeared several times more obvious deflection, and accompanied by corrective behaviour.

There are differences in the changes of earth pressure gauges during the three corrective time periods. The earth pressure gauges with decreasing results are mainly GF1, followed by GF2 and GF5; the earth pressure gauges with increasing results are mainly GF4, followed by GF3. Combined with the location of the earth pressure gauges, it can be inferred that the sinkhole is mainly tilted to the direction of GF4 in the process, and the earth pressure suffered by the sinkhole in this area is increased to the direction of passive earth pressure, and the earth pressure on the opposite side is decreased to the direction of active earth pressure. After the corrective treatment, the earth pressure tends to average. In addition to this, there is an opposite pattern in the change of data of each earth pressure gauge in the smaller fluctuations occurring in each time period. The initial values of the earth pressure gauges averaged 18 kPa and 40 kPa at the end of the period, and the increase increased towards the end of the period.

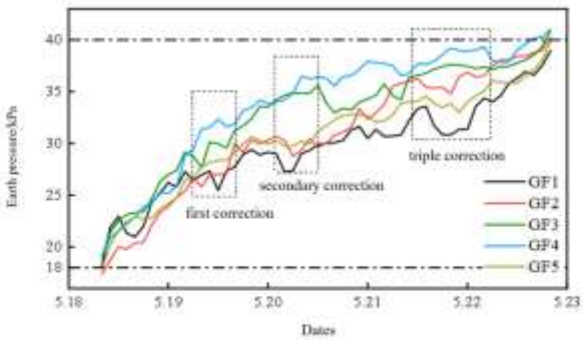


Figure. 6 Change in first subsidence data for layer I soil pressure gauge

The changes in the monitoring data of the soil manometer in layer I during the second subsidence period are shown in Fig. 7, and the frequency of collection during this period was higher than that during the first subsidence period. The initial average value of the earth pressure gauges during this period was 48.4 kPa, which was higher than the end value of the previous period. Overall, during the second sinking of the sinkhole, the data of each earth pressure gauge in layer I were closer, and the data gap between earth pressure gauges was the smallest during the small period of time when the excavation and sinking began. As the excavation continued to proceed to a deeper depth, the stable stratigraphic environment in which the sinkhole was originally located was affected, which, together with the sensor's own sensitivity, led to constant fluctuations in the monitoring results of the earth pressure gauges. The structural deflection and correction of the sinkhole due to the uneven settlement on site are also reflected in the different time periods of monitoring, and the changes in the results can better reflect the dynamic force changes of sinkhole sinking.

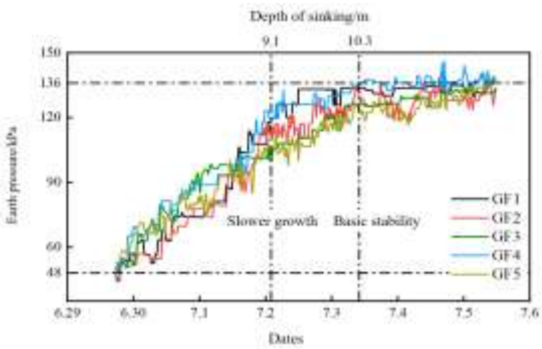


Figure. 7 Variation of secondary subsidence data of layer I soil manometer

Starting from sinking to about 9.1m, the trend of increasing soil pressure was slowed down. During the excavation process, the water content of the stratum increased, and under the influence of the groundwater level and seasonal precipitation,

International Water and Irrigation
Volume 44 Issue 1 (2025)
ISSN: 0334-5807
Pages 283- 292

there was water surge in the well, and the buoyancy of the sinkhole increased, slowing down the sinking speed. Thereafter, the pumping efficiency was improved on site to ensure the smooth sinking of the sinkhole.

The sinking reached approximately 10.3m, at which point the sinking work was nearing completion. There was more water inside the well, and along with the introduction of pumping equipment inside the well and the closing work of the surrounding fill, the soil changes on the outer wall of the sinkhole also gradually returned to stability. The monitoring results of the earth pressure gauge also fluctuated up and down within a certain range, and from the overall view of the period of time since then, it did not show any obvious increase or decrease. At the completion of sinkhole sinking, the average monitoring value between earth pressure gauges was about 136.2kPa.

4. Numerical modelling studies

4.1 model composition

The size and depth of the stratum selected for sinkhole operation need to be determined according to the size of the sinkhole structure, too small a stratum volume can't fully demonstrate the influence range of the interaction between the two, while too large a stratum volume will increase the difficulty of calculation. Considering the actual influence range of sinkhole construction, the length and width of the soil body are set at 50m, the depth is 30m, and the area is pre-divided, as shown in Figure 8.

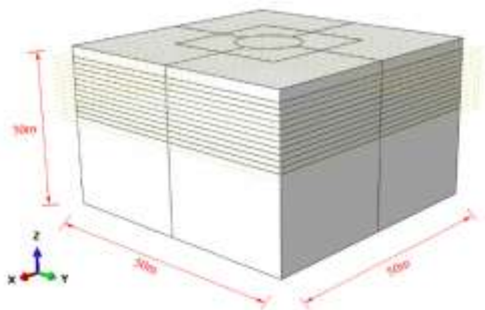


Figure. 8 Modelled stratigraphy

The structure of the sinkhole consists of external concrete and embedded steel cage, the wall thickness of the sinkhole is 1m, and there is a 0.2m protective layer on both sides of the cage, the height of both of them is 13m. The sinkhole is divided into upper and lower parts due to the two times of sinking, and the steel cage has been embedded in the concrete. After establishing the model of each part, the sinkhole was placed in the soil body at 2m in the assembly module as shown in Fig. 3.40, in order to set up the analysis in the subsequent modules.

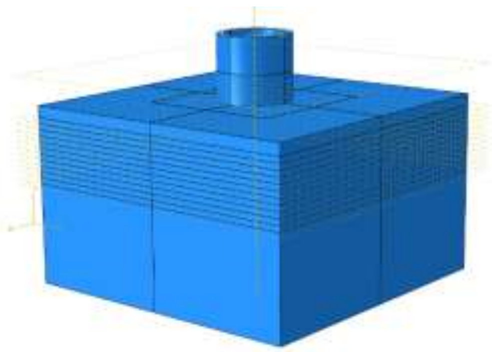
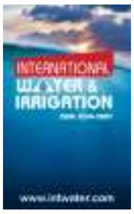


Figure. 9 Assembly drawing of immersed shaft

4.2 Material parameters

According to the previous ground investigation report and the indoor test results, considering that the actual mechanical parameters are similar between several strata, the strata are combined appropriately during the simulation, and the strata



are divided into three parts in the order of top to bottom, which are clay, silty clay and silt sand sandy clay in the order of clay, silty clay and silt sandy clay in the order of clay, silty clay and silt sandy clay in the order of clay. The mechanical parameters of each stratum and the structural components of the sinkhole are shown in Table 2. The set parameters were given to each stratigraphic stratification and sinkhole structure by generating cross sections.

Table 2 Mechanical parameters of materials

Stratigraphy/structure	Depth/m	Density/g-cm^3	Cohesion/kPa	Angle of internal friction/°	Modulus of elasticity/MPa	Poisson's ratio
loam	2	1.85	19	7	7	0.35
silty clay	11	1.78	20	8	18	0.38
silt sand sandwiched between clays	17	1.80	10	15	23.3	0.32
reinforcing cage	-	7.80	-	-	207000	0.25
concrete	-	2.20	-	-	30000	0.2

4.3 grid

A structured approach is used to grid the components as shown in Figure 10, with the soil body appropriately encrypted at a distance from the centre sinkhole and gradually thinned out near the edges. In terms of cell type, hexahedral cell C3D8R is used for the soil body and the concrete shell of the sinkhole, with a total of 59,815 cells for the soil body and 2,440 cells for the concrete. Since the shape set during the modelling of the reinforcement is linear, the truss T3D2 is selected as the cell type for the mesh division, and a total of 35724 cells are divided.

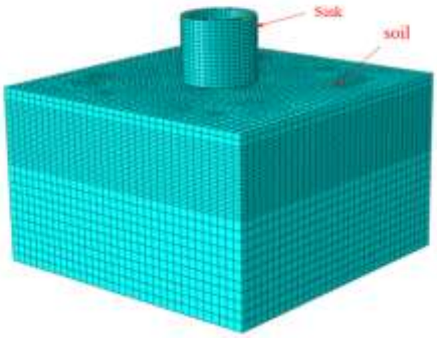
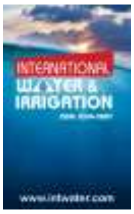


Figure. 10 Grid division diagram

4.4 simulation process

The setup of the analysis step of the simulation process consists of three main parts: ground stress equilibrium, generation of the caisson and sinking of the caisson. The first two parts are the first and second steps, and the sinkhole sinking is divided into 11 excavation and final stabilisation phases, which are the third to fourteenth steps of the analysis step. The excavation process is accompanied by a large amount of soil loss, and the failure and activation of the units in the simulation is achieved by the born-dead unit method. In the geostress equilibrium stage, the dead and alive unit method is used to deactivate the sinkhole placed in the starting position and activate it again after completing the geostress equilibrium; in the sinking process, the 1m deep soil to be excavated in each step is deactivated, and the sinkhole is sunk to occupy the original position.

For the boundaries of the soil body, the sides are constrained from displacement in the horizontal direction and the bottom from displacement in all directions, keeping the top free surface. Sinkholes placed into the soil body were constrained from displacement in all directions during the generation phase, and the constraints were removed at the start of sinking. Each time the sinkhole is sunk by 1m, the downward, increasing displacement parameter applied at the top of the sinkhole with the analysed step is also increased by 1m until it is fully sunk.



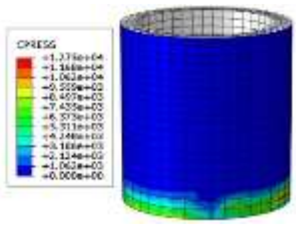
International Water and Irrigation
Volume 44 Issue 1 (2025)
ISSN: 0334-5807
Pages 283- 292

4.5 Analysis of results

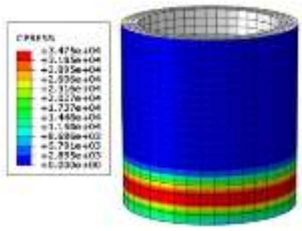
(1) Numerical simulation results

The contact pressure on the outer wall of the sinkhole can be investigated to reflect the earth pressure exerted due to the contact friction relationship between the sinkhole and the surrounding strata during the sinking process. The contact pressures of the sinkhole at different analysis steps are intercepted and shown in Fig. 11. The earth pressure on the outer wall of the sinkhole roughly increases with the depth of entry, and the area of influence increases as well. The coverage of the contact pressure, which is often greater than the actual depth of entry of the sinkhole in this analysis step, is mainly due to the transfer of the pressure on the outer wall that has been in contact with the soil during the simulation calculation. During the calculation process, the magnitude of the pressure at the junction will increase rapidly at the beginning, and as the analysis proceeds, the model tends to stabilise and the pressure gradually decreases again, stabilising after the iterative calculation is completed.

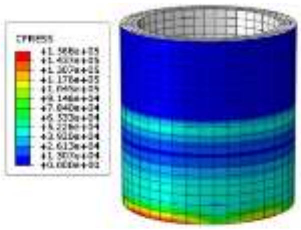
Considering that the difference in mechanical properties of nodes at the same depth is small in the simulation environment, a node path is created along the vertical direction in the outer wall, and the contact pressures on the nodes on the path are extracted at the end of the different sinking analysis steps in order to study the change in the magnitude of the earth pressure on the sinkhole during the sinking process, which is plotted as shown in Fig. 12.



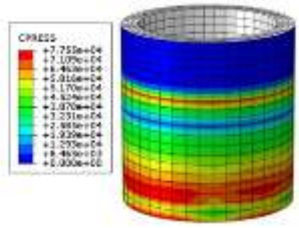
（a） ex-1contact pressure



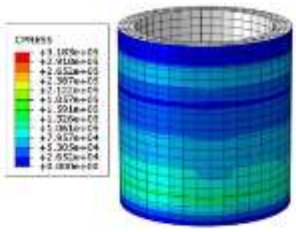
（b） ex-3contact pressure



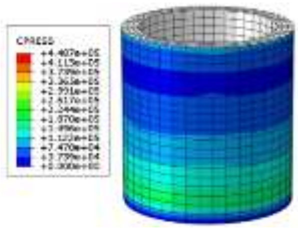
（c） ex-5contact pressure



（d） ex-7contact pressure



（e） ex-9contact pressure



（f） ex-11contact pressure

Figure. 11 Contact pressure cloud of sinkhole sinking

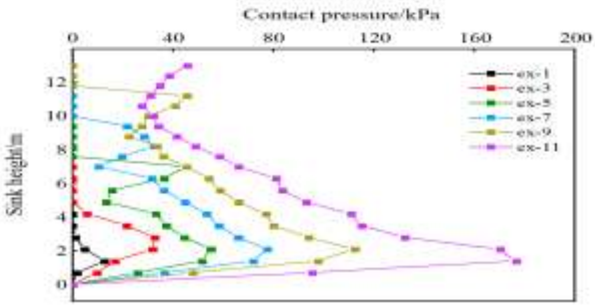


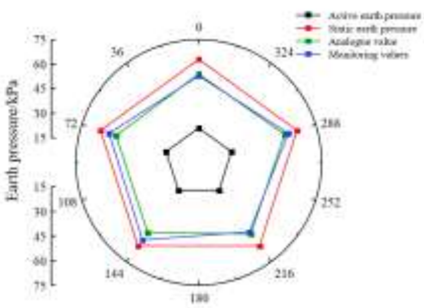
Figure. 12 Sinkhole contact pressure at different depths

In the excavation stages from ex-1 to ex-3, the variation of contact pressure with depth is roughly in the shape of a spoon, except that most of the unincorporated outer wall is not subject to pressure, and the rest of the section shows the lowest at the top and bottom, and the highest in the middle depth. At the end of stage 3, the maximum value of contact pressure is 32.70kPa, located at 2.8m from the bottom of the well, at this time, the depth of the sinkhole into the soil is 7m, and the point of maximum value has been shifted upwards.

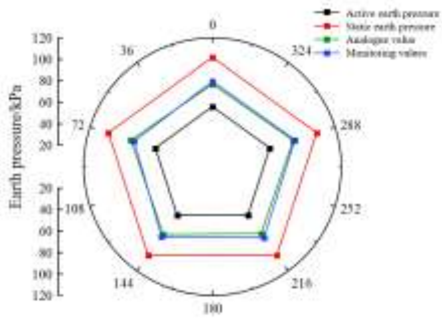
Starting from stage ex-5, the trend of contact pressure changes from a spoon shape to a bimodal shape, with a second pressure peak. at the end of stage ex-5, the extreme value of contact pressure at depth is 55.01kPa, 2.1m from the bottom of the well, and the extreme value at shallow depth is 45.46kPa, 6m from the top; the extreme value of contact pressure at depth is 77.47kPa, 2.1m from the bottom of the well, and the The shallow extreme value is 32.44kPa at 2.1m from the bottom of the well, 4.8m from the top; the deep extreme value of ex-9 stage is 112.28kPa at 2.1m from the bottom of the well, the shallow extreme value is 45.52kPa at 1.8m from the top; the deep extreme value of ex-11 stage is 176.28kPa at 1.4m from the bottom of the well, and the shallow extreme value is 45.69kPa, which is located on the top of the sunken well at this time.

Comparison with measured values in the field

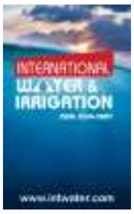
Select the I layer points of field test and simulation analysis points for comparison, both of them are regarded as positive pentagonal distribution, the drawing is located in the position from GF1 and M1 is set as 0 °, and every 72 ° in the anticlockwise direction is set as the next point to keep the same. Take the sinkhole sinking process at depths of 4m, 6m, 8m and 10m for comparative analysis, considering that the soil body has a tendency to move towards the well in the process of excavation and sinking, it is considered that the earth pressure on the sinkhole is closer to the active earth pressure. The static earth pressure and Rankine's active earth pressure calculation formula were chosen as the theoretical results for comparison, and combined with the simulation and monitoring data at that depth. The results of the soil pressure comparison at different depths for each point are shown in Figure 13.



(a) Depth 4m



(b) Depth 6m



(c) Depth 8m (d) Depth 10m

Figure 13 Comparison of soil pressure values at different depths

Comparison of the earth pressure at different depths intuitively shows that both the monitored and simulated values are between the static and active earth pressure, verifying the previous interval assumption about the magnitude of earth pressure. During the sinkhole excavation and sinking process, the soil at the original location was removed, and for the soil below, it was equivalent to losing the overlying load, and there was an unloading rebound, which led to a bulge at the bottom of the pit. During this process, the soil located in the periphery will also have a tendency to move towards the well, from which it is assumed that the soil pressure applied during sinking of the sinkhole is biased towards the active soil pressure.

At each depth location, the simulated and monitored values are relatively close to each other, which to some extent proves the informativeness of the simulation results to the monitoring data. The active earth pressure on the sinkhole at the depth of 4m is 21kPa, and the average values of the simulation and monitoring are 54kPa and 55.7kPa. The monitoring values at 72° and 144° are a bit higher than the simulated values by 8.5% and 10.4%, respectively, and the simulated values are 157.1% higher than the active earth pressure values, which is nearer to the static earth pressure at this time.

The active earth pressure at depth 6m was 56kPa, with simulated and monitored mean values of 78kPa and 79.9kPa. The monitored value at 216° was 6% above the simulated value, a smaller proportion than at depth 4m. Here the simulated value is 39.3% above the active earth pressure value and begins to approach the active earth pressure.

When sinking to a depth of 8m, the active earth pressure increased to 83kPa, the average values of the simulated and monitored values were 113kPa and 110.6kPa respectively, and the monitored value located at 216° was higher, 6.3% higher than the simulated value. The simulated value at this depth is 36.1% higher than the active earth pressure, further reducing the gap with the active earth pressure.

At the depth of 10m, the active earth pressure is 118kPa, and the average values of earth pressure simulation and monitoring are 137kPa and 134.2kPa respectively, and the monitoring value is basically smaller than the simulation value. The simulated value is 16.1% higher than the active earth pressure value. Combined with the distance between the folded lines in the figure, it can be seen that the simulated value is the closest to the monitored value at this time and has the smallest difference with the active earth pressure.

From the four depths of the earth pressure changes in the figure, it can be shown that the numerical simulation has a good validation effect on the monitoring results. At the same time, according to the rule of change, it is assumed that if the sinkhole continues to sink, the size of the earth pressure may further converge to the active earth pressure.

5. Discussion

The earth pressure monitoring data has been fluctuating throughout the construction process. Soil pressure with the increase of the depth of the soil can be roughly divided into three stages of change, the initial approximate linear growth, in the sinking to a certain depth, along with the well water and pumping behaviour, the growth slows down, near the completion of the almost stable, the soil pressure is no longer a significant increase in the final depth of about 10m at the point of measurement of the soil pressure average value of 136.2kPa. This law of change in the depth of the monitoring of the level

International Water and Irrigation
Volume 44 Issue 1 (2025)
ISSN: 0334-5807
Pages 283- 292

of the larger performance is more obvious, the depth of smaller monitoring level is weaker. This pattern of change is more obvious in the monitoring level of larger depth, and weaker in the monitoring level of smaller depth.

With the increase of sinking depth, the shape of the earth pressure curve at each point along the height of the sinkhole gradually changes from a spoon shape to a bimodal shape, and the maximum earth pressure is located at a certain height from the foot of the blade; the earth pressure on the outer wall of the sinkhole increases with the increase of depth, and the comparative analysis at specific depths shows that the simulated values and the monitored values are more in line with each other, which are between the active earth pressure and the static earth pressure, and are closer to the active earth pressure with the increase of depth gradually. Active earth pressure.

Refrences

[1] B XU Peng YU Binquan,CHEN Chuanchan. Pipe jacking construction technology [M]. Beijing:People's Traffic Press,1998.

[2] SONG Weining,GE Chunhui. Discussion on the approximate calculation method of recoil wall load in pipe jacking project[J]. Special Structures,1995,12(4):31-35.

[3] calculation for the load at thrust wall during pipe jacking project[J].Special Structures,1995,12(4):31-35.

[4] WANG Hengdong,GE Chunhui,WANG Daling,et al. Internal force analysis of circular sinkholes under jacking force[J]. Special Structures,2001,18(2):5-7.

[5] XIA Mingyao,WANG Bingqian,WANG Daling,et al. Calculation and design of internal forces in the construction and jacking phases of a circular diaphragm wall pipe jacking shaft[J]. Journal of Tongji University,1989,17(1):11-20.

[6] Wei Gang,Xu Riqing,Song Jinliang.Research on the calculation method of soil resistance in circular working well of SMW method[J]. Journal of Zhejiang University:Engineering,2005,39(1):98-102.

[7] Yu Jianjun. Settlement control technology around large Sink construction[J]. Building Construction,2012,34(05):481-483.