Influence of Groundwater on the Deformation During Foundation Pit Excavation and Finite Element Analysis

Jiangsheng Xie [1, a], Jiayu Li[2,b]

[1]China Railway 20th Bureau Group Co., Ltd.,Xi'an 710018, Shanxi, China
[2]School of Civil Engineering, Xi'an Univ. of arch. & Tech., Xi'an 710055, China

[a]e-mail: 1543455186@qq.com
*Corresponding author: [b]18203443327@163.com

Abstract. With the increase of foundation pit excavation depth, the influence of groundwater on the horizontal displacement of the envelope structure during foundation pit excavation is becoming more and more obvious. The coupling of the sedimentation mechanism and the stress field is analyzed, the deformation of the excavation is monitored and the detection results are analyzed. Taking section 5 of Suzhou Chunshenhu Road rapid transformation project as an example, ABAQUS finite element analysis software constructs a two-dimensional numerical model of deep foundation pit and adjacent buildings, which simulates the influence on the surrounding environment in the whole construction process of excavation and support precipitation. Through the theoretical analysis of the seepage field and stress field related to the foundation pit precipitation, the actual settlement can be effectively reacted and described.

Keywords: foundation pit precipitation; coupling analysis; engineering detection and numerical simulation

1 Introduction

In recent years, with the rapid development of the national economy, the construction of urban infrastructure has also been accelerating. In particular, the urbanization process in coastal areas is accelerating, which brings great pressure on traffic and housing. With the acceleration of large-scale urban underground municipal traffic engineering and high-rise buildings, it is urgent to improve the design and construction level of deep foundation pit. High-rise buildings or traffic engineering are generally located in the building dense, densely populated areas, due to the complexity of hydrogeological conditions and the characteristics of urban center building dense, require engineering decision makers to pay more attention to the displacement and ensure the safety of foundation pit construction, which is a hot topic of geotechnical engineering research. It has aroused the research interest of many scholars.Sun Kguo et al. [1] studied the influence of different forms of water-rich karst caves on the stability of foundation pit. Zhang Wentao et al. [2] studied the deformation and force change law of the foundation pit supporting structure in the construction process through three-dimensional finite

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unit simulation, and compared it with the on-site monitoring results. On the basis of field monitoring, Chen Zhaoyang et al. [3] used theoretical and numerical means to study the influence of the permeability coefficient of the foundation pit on the envelope structure at high water level.Tang Lin et al. [4] used the finite element model to compare and analyze the influence of precipitation of single foundation pit and foundation pit group under the condition of anhydrous formation and water-rich formation, as well as the change of the groundwater level outside the pit on the deformation of the foundation pit retaining structure. Sun Haixia et al. [5] used ABAQUS to analyze the 3 D numerical simulation of groundwater seepage and excavation in the foundation pit. Lu Mingtao et al. [6] reached some guiding conclusions conducive to the safety of foundation pit according to the main monitoring results of a deep foundation pit in Wuhan.Huo Runke et al. [7] Through comprehensive analysis and evaluation, we obtained the change law of soil and support during the excavation of deep foundation pit. Dong Xiao et al. [8] verified the feasibility and reliability of automatic displacement monitoring according to the principle, method and field monitoring scheme of light rail piers. Zhou Nianqing et al. [9] On the basis of the on-site pumping test, the three-dimensional finite difference method was used to simulate the precipitation of the foundation pit by inversion of the permeability parameters. Zu Jiangluo et al. [10] believed that three-dimensional finite element numerical simulation is the basic theory of structural optimization design of deep foundation pit precipitation engineering

In this paper, the coupling of the sedimentation mechanism and the seepage field and the stress field in the precipitation process are analyzed theoretically, the deformation in the excavation process is monitored and the detection results are analyzed With the background of section 5 of Suzhou Chunshenhu Road Rapid transformation project as the background, using ABAQUS finite element analysis software, a two-dimensional numerical model suitable for the foundation pit and adjacent buildings is constructed, and the impact on the surrounding environment in the whole construction process of excavation and support precipitation is simulated. Through the theoretical analysis of the changes of seepage field and stress field related to foundation pit precipitation, the research results can provide the basis and guidance for the safe construction of similar foundation pit.

2 Basic theory of the Influence of Seepage on Foundation pit

2.1 Project Overview

Section 5 of Suzhou Chunshenhu Road rapid reconstruction project starts from the east of Sujiahang Expressway, and the total length of the main tunnel is 4.47km. K11 + 110~K11 + 740 is in the lake area. Using the method of steel plate pile, the groundwater is drained and then excavated at the bottom of the lake. The depth of the foundation pit is 1.17~24.63m, among which, the maximum depth in Linjia Road is 24.63 meters, and the maximum depth in the middle of the lake is 10.54 meters.

The hydrological conditions of this project are more complex. The distribution of groundwater can be divided into three types: underground diving, micro-confined water and confined water. The specific distribution of groundwater is as follows:

Diving is mainly distributed in shallow clay, water level depth 0.70~4.10m stable water depth 0.30~4.30m and elevation 0.48~2.09m, the water level fluctuates with seasonal climate.

The slightly confined water is mainly filled with silt layer and silty layer with silty layer, which is generally rich in water and has good water permeability. The burial depth and thickness of the aquifer have some fluctuations, with buried depth between 0.7~20.4m and thickness between 0.7~14.4m. According to the analysis of the pumping test results, the elevation of the microconfined water head is located at 1.23~1.34m. The main supply sources of the confined water layer are the vertical infiltration of shallow groundwater and the transverse runoff of groundwater. Civil well exploitation and groundwater transverse runoff are the main drainage methods.

The confined water is mainly located in silty clay, which is generally water-rich. The water level of confined water generally changes by about 1m, and the supply source is mainly micro-confined water supply and underground runoff supply. Underground runoff and manual suction are the main drainage methods.

2.2 Analysis of Sedimentation Mechanism During Precipitation in Foundation Pit

Surface subsidence has been studied for many years, and many theories and viewpoints have been put forward today. However, the basic principle of ground subsidence induced by foundation pit precipitation is consistent, that is, groundwater drainage leads to the decrease of formation water level, the decrease of pore water pressure, and then soil compaction and consolidation, and ground subsidence. In the process of foundation pit precipitation, the ground subsidence produced by the underconsolidated soil layer and the normal consolidated soil layer is relatively large. For the superconsolidated soil layer, when the effective stress after precipitation is less than the initial maximum consolidation stress, only a small settlement occurs and elastic deformation occurs. After the precipitation, the water level recovers, and the formation will partially rebound under the buoyancy of water; When the groundwater level depth caused by precipitation in the middle of the foundation pit is large and the effective stress exceeds the maximum consolidation stress in the early stage, the formation will produce large settlement with the increase of effective stress, which is plastic deformation.

3 Simulation Study of Foundation Pit Excavation Process

3.1 Coupling Analysis of Seepage Field and Stress Field During Precipitation

The pore water pressure in soil has an impact on the balance between soil particles, and reflects the very close joint effect between the mechanical action of soil and the infiltration of groundwater, that is, the infiltration of groundwater affects the change of the stress state of soil. This is the result of osmoation and stress.In this paper, we derive the continuity equation of 3 D unstable seepage based on the continuity of water flow in saturated soil, and then the stress equilibrium equation. The basic equation of 3 D unstable seepage-stress coupling with displacement and pore pressure as the unknown number is established.

According to Darcy's law, starting from the continuity of saturated soil flow, the compressibility of the soil per unit time is added to the surface of the soil, ignoring the compressibility of water

$$\frac{\partial}{\partial t}(\varepsilon_v dxdydz)=\frac{\partial(q_x dydz)}{\partial x}+\frac{\partial(q_y dxdz)}{\partial y}+\frac{\partial(q_z dydx)}{\partial z} \tag{1}$$

Combining the soil geometric equations can be obtained

$$\frac{\partial}{\partial t}\left(\frac{\partial w_x}{\partial x}+\frac{\partial w_y}{\partial y}+\frac{\partial w_z}{\partial z}\right)-\frac{1}{\gamma_w}\left(K_x\frac{\partial^2 u}{\partial x^2}+K_y\frac{\partial^2 u}{\partial y^2}+K_z\frac{\partial^2 u}{\partial z^2}\right)=0 \tag{2}$$

Write the matrix expression as follows:

$$\{M\}^T[\partial][K][\partial]^T\{M\}u-\frac{\partial}{\partial t}\{M\}^T[\partial]\{w\}=0 \tag{3}$$

Equation 3 is the expression of the displacement and the pore pressure by using continuous equations. At any point in the saturated soil, the hole pressure and displacement meet the stress balance and permeability continuous equation. The basic equation of unstable seepage-stress coupling:

$$\begin{cases} -G\nabla^2 w_x-\dfrac{G}{1-2v}\cdot\dfrac{\partial}{\partial x}\left(\dfrac{\partial w_x}{\partial x}+\dfrac{\partial w_y}{\partial y}+\dfrac{\partial w_z}{\partial z}\right)+\dfrac{\partial u}{\partial x}=0 \\ -G\nabla^2 w_y-\dfrac{G}{1-2v}\cdot\dfrac{\partial}{\partial y}\left(\dfrac{\partial w_x}{\partial x}+\dfrac{\partial w_y}{\partial y}+\dfrac{\partial w_z}{\partial z}\right)+\dfrac{\partial u}{\partial y}=0 \\ -G\nabla^2 w_z-\dfrac{G}{1-2v}\cdot\dfrac{\partial}{\partial z}\left(\dfrac{\partial w_x}{\partial x}+\dfrac{\partial w_y}{\partial y}+\dfrac{\partial w_z}{\partial z}\right)+\dfrac{\partial u}{\partial z}=0 \\ \dfrac{\partial}{\partial t}\left(\dfrac{\partial w_x}{\partial x}+\dfrac{\partial w_y}{\partial y}+\dfrac{\partial w_z}{\partial z}\right)-\dfrac{1}{\gamma_w}\left(K_x\dfrac{\partial^2 u}{\partial x^2}+K_y\dfrac{\partial^2 u}{\partial y^2}+K_z\dfrac{\partial^2 u}{\partial z^2}\right)=0 \end{cases} \tag{4}$$

According to this equation, the displacement boundary condition and the seepage field and stress field.

3.2 Numerical Model of Foundation Pit Excavation and Precipitation

In this simulation, the deep foundation pit and surrounding buildings, and the whole process is calculated. Considering the radial length of the tunnel is much larger than the pit cross section, a two-dimensional finite element model is proposed.In the calculation, the whole process of osmotic consolidation is considered, because the influence range of precipitation is much larger than the influence range of excavation, so the spatial effect and the large well hypothesis are combined.Assuming that the foundation pit is a large incomplete well, the precipitation process in the pit is regarded as the precipitation process of diving intact well and confined incomplete well. The Qiubuyi formula is used to calculate the influence range of precipitation as follows. Finally, the horizontal dimension of the model is set to 10 times the depth of the foundation pit, with a geometric dimension of 238.6m (x) 93m (y).The model is shown in Figure 1.

$$R = 10S_w\sqrt{K} = 10\times13\times\sqrt{0.684} = 107m \tag{5}$$

In the above equation, R is the influence radius range(m),S_w is the decreasing depth of the water level in the well(m),K is the permeability coefficient of the confined water layer soil(m/d).

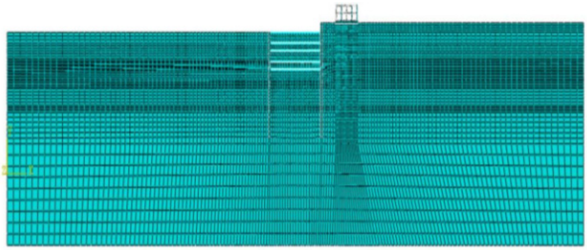

Fig. 1. Schematic representation of the FE model

Referring to the engineering hydrogeological situation, the soil is layered according to the actual situation, and the Moore Cullen constitutive model and CPE 4 P four-node plane seepage stress coupling unit are adopted. According to the stratigraphic data, the section involves 12 soil layers. However, considering the feasibility of the model calculation, the soil layers with similar properties are combined to model, so there are 10 soil layers in the model.From top to bottom are 3-1 silty clay, 4-2 silt sand layer, 5 silty clay, 6-1 clay, 6-2 silty clay, 6-3 silt sand layer, 7-1 silty clay, 7-2 clay, 7-3 silty clay, 8 clay with silty clay. Specific material properties are shown in Table 1.

Table 1. List of tunnel engineering settings

solum	thick-ness/m	se-vere/kN·m^3	modulus of elasticity/MPa	internal friction angle	cohesion /kPa	Poisson's ratio
3-1 silty clay	4.5	19.5	15	15.5	54.2	0.33
4-2 silt sand layer	3.5	18.8	50	28.8	5.2	0.32
5-1 silty clay	8	18.9	41.6	15.8	22.8	0.35
6-1 clay	2.5	19.7	64.6	15.4	54.7	0.31
6-2 silty clay	7	19.2	50.4	15.4	27	0.33

6-3 silt sand layer	1.5	19.5	120	28	6	0.29
7-1 silty clay	1.5	19.1	45.4	14	23	0.33
7-2 clay	4	19.1	83.2	23.5	8.9	0.31
7-3 silty clay	9	19.0	75	14.7	25.8	0.33
8 clay with silty clay	42.5	19.4	100	15.2	33	0.33

According to the hydrogeological report, the groundwater on the project site is divided into loose shallow hole diving and loose rock hole pressure (micro) water, and the submersible head elevation is-1m. The microconfined water is mainly distributed in the silt and silt layer, and the head elevation is set as + 1m. The confined water is mainly distributed in the silt and silt layer, and the head elevation is set at-2m. The permeability coefficient of each soil layer is shown in Table 2.(Micro) confined water is simulated by setting the pore pressure limit in the model.

Table 2. The permeability coefficient of the soil layer

solum	Vertical KV(m/h)	Horizontal KH(m/h)	Permeability classification
3-1 silty clay	8.28E-06	9.36E-006	Micropermeable
4-2 silt sand layer	4.32E-03	4.04E-03	Medium permeable
5-1 silty clay	2.63E-04	2.95E-04	Micropermeable
6-1 clay	2.92E-05	3.28E-05	waterproof
6-2 silty clay	1.73E-04	1.94E-04	Micropermeable
6-3 silt sand layer	3.60E-03	4.68E-03	Medium permeable
7-1 silty clay	3.20E-04	3.53E-04	Micropermeable
7-2 clay	4.68E-02	4.76E-02	Medium permeable
7-3 silty clay	1.44E-04	1.44E-04	Micropermeable
8 clay with silty clay	1.48E-04	1.62E-04	Micropermeable

When simulating the adjacent buildings outside the foundation pit, the building is physically modeled according to the actual geographical location and structure map, and placed at 10-17m outside the foundation pit. According to the Technical Regulations for Concrete Structure of High-rise Buildings (JGJ 3-2010): " At present, in reinforced concrete structure high-rise buildings, through constant load and live load caused by unit area gravity, frame and frame-shear wall structure is about 12 kN/m2-14 kN/m2, shear-wall and cylinder structure is about 13 kN/m2-16 kN/m2, but, in these data, the proportion of live load is about 2 kN/m2 to 3 kN/m2, it only accounts for 15% to 20% of the total gravity, the adverse distribution of live load has little impact on it."The dormitory building is a two-story reinforced concrete structure building, and the corresponding load is applied according to the specification, and the material is C30 concrete.

The underground continuous wall installed on both sides of the foundation pit is simulated with solid waterproof components. In this paper, the contact surface ContactPair instruction is used to calculate the contact surface of the wall and the ground. The contact surface has no thickness and the sliding is very small, so the mol-Collombi model of 0.3 is adopted. The Mohr-Coulumb algorithm applies the penalty function algorithm. In this paper, B21 without thick beam unit is used to simulate the force of reinforced concrete and steel pipe, and its mechanical properties are analyzed.The column is also simulated by the solid unit of the line elastic material. Because the horizontal distance between the support and the column is large, the horizontal support of the same column and the same height in the calculation should be equivalent to the continuous wall. For lateral support, in the two-dimensional equivalent simplification, the compressive stiffness of the actual cross section of the concrete should be consistent with the compressive stiffness of the equivalent rear cross section, that is, the corresponding size or stiffness should be adjusted after the calculation of equal stiffness. At the same time, the contacts between the wall, column and transverse support are connected by the PIN joint method in ABAQUS.

On this basis, the method of excavation and rainfall is the simulation of the whole process.① Step 1: Initial balance of the stress. At this stage, other elements besides the original soil and the corresponding contact surface are removed, so that the pore pressure of the soil reaches a natural stable state.② Step 2: start the contact relationship between the underground pouring wall structure unit and column and soil, first precipitation, excavate the first soil layer, apply the first reinforced concrete support; ③ Step 3: secondary drainage, secondary excavation, secondary steel pipe support; then drainage, excavate the lower soil, use steel pipe support until excavation to the bottom of the foundation pit.In the construction process of construction, three layers of soil should be seen to the bottom, and after the foundation pit appears, pour the cushion in time to accelerate the closure of the foundation, and control the deformation of the foundation pit. The thickness of the cushion is about 200mm. In the simulation process, the material properties of the soil in the cushion area are strengthened in the corresponding analysis stage to realize the simulation effect of the cement and soil reinforcement cushion layer. When setting the boundary conditions, the left and right sides of the model limit the horizontal displacement, and the pore water pressure boundary is set to simulate the external recharge of groundwater. The bottom is set with horizontal and vertical constraints, and is set to be waterproof. In the pre-precipitation process before the lower soil excavation, the precipitation process is simulated by setting the pore pressure at 1m below the excavation surface to 0. Similarly, the pore water pressure of the confined water layer is reduced when excavating the third layer of soil to simulate the step-down process.

3.3 Analysis of the Numerical Simulation results

The deep horizontal displacement of CX58 adjacent building was simulated, and the displacement curve is shown in Fig2.

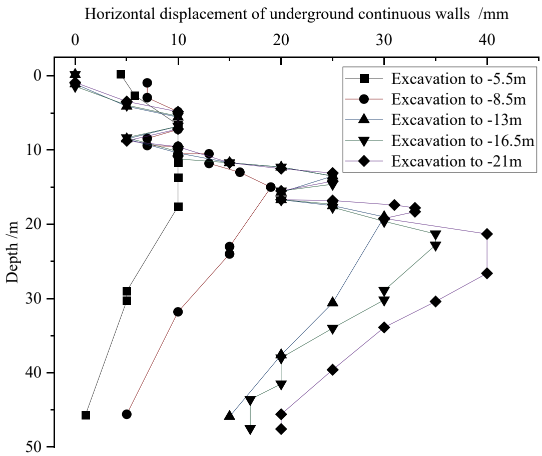

Fig. 2. Simulation value of the horizontal displacement of the underground continuous wall

As shown in Figure 2, at the initial stage of foundation pit excavation, the curve of the horizontal shift is relatively smooth at the beginning of construction, and the horizontal displacement from the top and bottom to the pit is small, while at the excavation surface is larger, with the overall shape of "convex". However, with the gradual increase of the excavation depth, the lateral migration rate is significantly slowed down from-12m to-20m, which is basically controlled within a certain range, and the trend of slight retraction at-15.5m and-20m. This depth range is consistent with the depth of the horizontal support layout of the foundation pit. At the end of the excavation, the bottom of the pit below the underground continuous wall appear large horizontal displacement, the maximum horizontal displacement at the pit of about 0.5m, at this time because of the deep soil has no effective support structure support, horizontal displacement curve is no longer smooth, into a shallow with the depth increases, the middle change is not obvious, deep spindle-shaped three-stage curve.

4 Measured Study of Deformation During Foundation Pit Excavation

4.1 Project Monitoring Scheme

Field monitoring refers to the observation and analysis of the rock and soil properties in the foundation pit. According to the excavation of the foundation pit and underground engineering construction, the displacement of the supporting structure and the surrounding environmental conditions change, the observation results will be fed back in time to guide the design and construction. Before the excavation of the foundation pit, an on-site monitoring program should be formulated, including the monitoring target, monitoring content, monitoring point layout, observation method, monitoring project alarm value, monitoring results processing requirements, monitoring results feedback system, and processing the monitoring results in time.It shall be implemented by qualified survey organizations, and shall report the monitoring results to the supervision, design and construction units in time. Where necessary, appropriate measures shall be taken on the basis of site monitoring. According to the design specifications and requirements, the monitoring scope of the project, the surrounding roads and pipeline buildings within 3 times the excavation depth are selected as the monitoring objects, and the cofferdam excavation method is adopted in the tunnel. The depth of the foundation pit is in the range of 1.17-24.63 meters, the largest range of Linjia Road is 24.63 meters, and the middle of the lake, 11.54-18.17 meters. Therefore, the foundation pit monitoring scope of this project is 11.0m~49.3m.

4.2 Analysis of Monitoring Results

224 oblique monitoring holes (No. CX1~CX224) are set on both sides of the foundation pit, and the spacing between the measuring points is about 20m. The following monitoring data of CX58 are sorted out and analyzed:

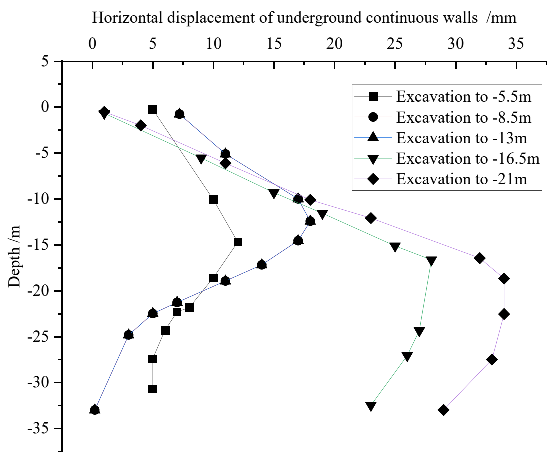

Fig. 3. The measured value of the horizontal displacement of the measuring point

As shown in Figure 3, the displacement of the underground continuous wall to the pit also gradually increases with the continuous excavation. The horizontal displacement of the underground continuous wall to the inside of the foundation pit is relatively small, but the displacement of the foundation pit excavation is very large, and there is a trend of large and small displacement at the middle ends. With the increase of the foundation pit depth, the transverse displacement velocity of the-12-20m foundation pit decreases and basically remains in a certain range. At the end of the excavation, the underground continuous wall near the bottom of the foundation pit had a large horizontal displacement. The maximum horizontal displacement is located near the bottom of the pit. The maximum side shift value is δm=34.96mm, approaching the control value of 0.18%he=36mm (he is the depth of foundation pit excavation).

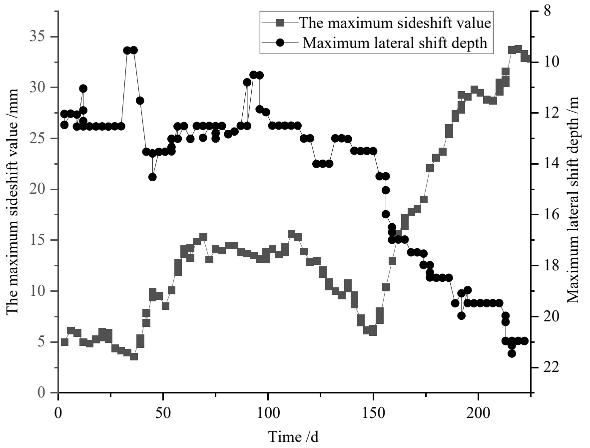

Fig. 4. Maximum horizontal displacement and position shift of the measurement point

As shown in Figure 4, in general, the maximum displacement increases with the depth of the excavation. Among them, the third layer of soil excavation is affected by the bottom of the pit pouring cushion layer. The maximum lateral shift value has some decrease, but increases sharply in the subsequent excavation of the fourth and fifth layers. The maximum depth of the lateral shift point also increases with the excavation depth. The maximum lateral displacement varies from 19.53mm (to-13m at-17m) at-17 m and 28.1mm (to-15.5m) at-19m to 34.96mm at-21.5m (to-21m), when the maximum lateral displacement depth is consistent with the pit excavation depth.

5 Conclusion

The theoretical analysis of the changes of foundation pit seepage field and precipitation stress field can be effectively responsive and described. Firstly, the finite element software ABAQUS is used to simulate the whole process of the precipitation excavation considering the influence of confined water. Secondly, the construction section of the main school building adjacent to the south side is comprehensively monitored, and the numerical simulation results are compared with the monitoring results, the underground continuous wall has a large horizontal displacement to the pit with the excavation, the maximum displacement depth gradually decreases with the excavation, and the numerical simulation method can better reflect the deformation trend and the influence of excavation on the surrounding environment.

Acknowledgments

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References

1. Sun, K.G., Zhen, Y.Z., Wei, Y. et al. (2023) Influence Law and Analysis of Foundation Pit Stability in Water-bearing Karst Area. J. Modern Tunnelling Technology., 60(1): 149-158+194.
2. Zhang, W.T., Qi, C.Q., Zhou, Z.F. et al. (2022) Study on Lakebed Deep Foundation Pit Bracing Structure Deformation and Weighted Features. J. Coal Geology of China., 34(1): 62-68,80.
3. Chen, S.L., Li, M., Gao, J.L. et al. (2022) Study on the Influence of Groundwater Level and Stratum Permeability Coefficient on Foundation Pit. J. Journal of East China Jiaotong University., 39(1): 59-66.
4. Tang, L., Cui, L.G., Wang,J.L. et al. (2022) Study on the influence of precipitation and water level change in excavation of foundation pit group in water-rich strata evaluation. J. Shanxi Architecture., 48(11): 68-72.
5. Sun, H.X., Zhang, K., Chen, S.L. et al. (2015) 3D elastic-plastic numerical simulation on deep foundation pit excavation with considering dewatering effect. J. Journal of Shenyang University of Technology., 37(5): 588-593.
6. Lu, M.T., Xing, X.K., Song, Z.P. (2011) Monitoring and Analysis on a Deep Foundation Pit Engineering in Wuhan. J. Journal of Water Resources and Architectural Engineering., 9(04): 109-111+123.
7. Huo, R.K., Yan, M.Y., Song, Z.P. (2011) The Monitoring and Numerical Analysis of Deep Foundation in Subway Station. J. Journal of Railway Engineering Society., 28(05): 81-85.
8. Dong, X., Xing, X.K., Song, Z.P. et al. (2010) Real-time monitoring technology and engineering application of the excavation construction impact on the existing near-by light rails bridge piers. J. Journal of Changchun Institute of Technology(Natural Sciences Edition)., 11(02): 42-46.
9. Zhou, N.Q, Vermeer, P. A., Lou, R. et al. (2010). Numerical simulation of deep foundation pit dewatering and optimization of controlling land subsidence. J. Engineering Geology, 114(3-4): 251-260.
10. Zhang, Z.J, Ying Y, Wu, Y.X., (2008). Finite element numerical simulation of three-dimensional seepage control for deep foundation pit dewatering. J. Hydrodynamic Research and Progress: English Edition., 20(5): 7.