Analysis of Influencing Factors on Internal Forces of Large-diameter Jacking Pipe Structures in Composite Formations

Bin Zhang[1,2,*], Xiaoxiang Chen[1,3], Jianwu Gong[4]

[1]Department of Civil Engineering, Xi'an Jiaotong University, Xi'an, 710049, China
[2]CHINA ENERGY ENGINEERING GROUP SHANXI ELECTRIC POWER ENGINEERING CO., LTD. Shanxi, Taiyuan, 350003, China
[3]POWERCHINA FUJIAN ELELECTRIC POWER SURVEY & DESIGN INSTITUTE CO., LTD. Fuzhou, Fujian, 350003, China
[4]School of Urban Construction, Wuhan University of Science and Technology, Wuhan, Hubei, 430081, China

*Corresponding author's e-mail:zhang@sepec.com.cn

Abstract. The design of the existing top pipe pipeline structure adopts a plane strain model and assumes that the pipe circumference is a homogeneous foundation soil. By selecting typical geological conditions for internal force calculation and reinforcement of the pipeline structure, if the established rock and soil physical and mechanical parameters in the engineering design are different from the actual situation, that may cause engineering quality problems. Based on a large-diameter pipe jacking project in a composite formation, the load structure method and the formation structure method were used to analyze the variation law of the internal force of the pipe joint under different geological conditions on the pipe sidewall. The results showed that the better the physical and mechanical parameters of the soil on the pipe side and the lower the groundwater level, the greater the calculated internal force of the pipes. When the top of the pipe is covered with backfill soil, the greater the formation loss rate, the greater the inner force of the jacking pipe structures. During construction, the formation loss rate should be strictly controlled to ensure the safety of the pipeline structure.

Keywords: composite strata; soil lateral pressure; electric power tunnel; segment structure; influence law.

1 Introduction

According to the current Chinese standards [1][2], the load structure method is used for the jacking pipe structure design [3][4]. Since previous pipelines were mainly suitable for municipal pipeline network engineering, with small inner diameters, the active soil pressure on the lateral side of the pipes was assumed to be rectangular distribution, and its calculation results were relatively close to reality and simple, so it was widely adopted by engineering and technical personnel [2]. On the other hand, the inner

P. Xiang et al. (eds.), *Proceedings of the 2023 5th International Conference on Hydraulic, Civil and Construction Engineering (HCCE 2023)*, Atlantis Highlights in Engineering 26,
https://doi.org/10.2991/978-94-6463-398-6_35

diameter of the top pipe in power engineering is often greater than 2.0m [5], with the maximum reaching 5.0m [6], and it is also distributed in shallow underground spaces (0m~ -15m) [6][7]. Along the longitudinal direction of the pipeline, geological conditions within the height range of the pipeline often undergo changes in soil properties or distribution thickness, especially in various composite formations with soft upper and hard lower layers. The soil pressure on the side walls of the pipeline will exhibit complex distribution characteristics. At this point, if the active earth pressure at the center point of a circular pipe is still calculated using the provisions of Chinese standards such as CECS 246:2008, and the method of acting in the form of a rectangle on the side wall of the pipeline may result in significant deviations, which may lead to various quality and even safety issues that do not match the actual stress state of the pipes.

Huang Zhigang used finite element software to study the distribution law of the influence of steel pipe deformation on the soil lateral pressure of a particular ND2000 steel top pipe and corrected the calculation formula [8]. Based on current national standards, Yuan Li analyzed the trend of internal force values in the top pipe structure at different groundwater levels through a large amount of data calculation and suggested that the influence of groundwater level elevation should be comprehensively considered in the analysis of internal force in the top pipe structure [9]; Yang Xian analyzed the distribution characteristics of arch soil pressure under the mutual influence of double line jacking pipes for small spacing parallel top pipes [10][11]. The previous research on the distribution characteristics of soil pressure around the pipe jacking and its impact on the structure has achieved specific results, but it is still based on homogeneous soil layers. Further related research should be carried out for large-diameter pipe jacking projects in composite formations.

The project is based on the DN2000mm top pipe project of a 110kV cable line project in Shanxi Province. The impact of different composite soil layer distribution characteristics on the internal force of the pipeline is analyzed, and corresponding design suggestions are proposed to support the project's refined design and reference for the construction, disaster prevention, and reduction of related projects.

2 Project overview

A 110kV cable in Shanxi Province is laid in a pipe layout, and several sections of the urban main road are laid in DN2000 top pipe tunnels. The pipes are made of prefabricated reinforced concrete structures with a strength of C50 and a wall thickness of 200mm. Due to the safety distance requirements for crossing pipelines in the overlying soil layer, the thickness range of the soil cover for new power engineering top pipes is 5.0m to 10.0m.

2.1 Engineering geological and hydrogeological conditions

The geomorphic unit along the route is the alluvial plain on the east bank of the Yuhe River, with a flat terrain. The exposed strata along the way are mainly the Quaternary Upper Pleistocene and Holocene strata. According to the geological conditions revealed by the engineering survey, the lithology of the exposed strata within a depth range of 15m in this section is mainly:

① Miscellaneous fill soil: mottled, brownish yellow, mainly composed of silty clay, silt, gravel sand, and fine sand, mixed with construction waste, slightly wet, loose, with a thickness of 4.7-6.1m.

② Coarse sand: brownish yellow, mainly composed of quartz, feldspar, and mica, with a small amount of gravel, interbedded with thin layers of silty clay and lenses, partially interbedded with silty clay, with average particle size distribution, slightly wet, slightly dense, and a thickness of 5.9m to 7.3m.

During the survey, the groundwater level in this section was buried at a depth of 8.0m to 12.0m, with the highest possible water level of 6.0m. The physical and mechanical indicators of the primary rock and soil masses within the scope of pipe-jacking construction are detailed in Table 1.

Table 1. The distribution of strata and their leading physical and mechanical indicators within the scope of pipe-jacking engineering construction

Classification	γ (kN/m^3)	C(kPa)	φ(°)	f_{ak} (kPa)
① Miscellaneous fill soil	15.0	5.0	15.0	70
② Coarse sand	21.0	0	30.0	190.0

2.2 Distribution combination of typical pipe side soil

Due to the uneven distribution of strata and changes in pipeline burial depth, there are eight possible distribution combinations of soil on the pipeline sidewalls, denoted as combination I to combination VIII (Table 2):

Table 2. Combination of Pipe Side Wall Composite Strata

Stratigraphic combination type	Category of soil at the center of the pipeline	Groundwater burial	Water level description
I	① Miscellaneous fill soil	-9.0m	The groundwater lever is located below the pipes
II		-7.2m	The groundwater level is located at the center of the pipes
III		-6.0m	The groundwater level is located at the top of the pipes
IV		-4.0m	Groundwater is located at a certain height above the top of the pipes
V	② Coarse sand	-9.0m	The groundwater lever is located below the pipes
VI		-7.2m	The groundwater level is located at the center of the pipes
VII		-6.0m	The groundwater level is located at the top of the pipes
VIII		-4.0m	Groundwater is located at a certain height above the top of the pipes

3 Existing design methods for jacking-pipes

3.1 Calculation of soil lateral pressure using CECS 246 method

The pipe jacking technology originated from water supply and drainage engineering. Currently, the most influential and widely used standard in China is the CECS 246:2008 standard of the China Engineering Construction Standardization Association, which stipulates the calculation of soil lateral pressure as follows:

(1) When the pipeline is above the groundwater level, the standard value of lateral soil pressure can be calculated using the following formula for active soil pressure:

$$F_{h,k} = (F_{sv,ki} + \gamma_{si} D_1 / 2) K_a - 2C\sqrt{K_a} \tag{1}$$

Where $F_{h,k}$ is Lateral soil pressure standard value (kN/m^2), acting at the center of the pipeline, K_a is Active earth pressure coefficient, i.e. $K_a = tg^2$ (45 °- Φ/ 2).

(2) When the pipeline is below the groundwater level, the standard value of lateral soil and water pressure should be calculated using soil and water separation. The lateral pressure of soil should be calculated according to equation (1), and the effective weight should be taken as the weight. The groundwater pressure is calculated based on static water pressure, and the weight of water can be taken as 10kN/m^3.

3.2 Method for calculating internal forces in pipelines

According to standards such as CECS 246:2008 and DL/T 5481-2013, the pipeline structure adopts the load structure method. It assumes that the lateral active earth pressure is arranged in a rectangular shape along the lateral direction of the pipeline to calculate the internal force (Figure 1). The circumferential inner strength of the pipeline cross-section can be calculated using the following formula:

$$M = r_0 \sum_{i=1}^{n} k_{mi} P_i \tag{2}$$

$$N = \sum_{i=1}^{n} k_{ni} P_i \tag{3}$$

Where, M is the maximum bending moment design value of pipes cross-section (N·mm/m), N is the design value of axial force on pipeline cross-section (N/mm), r_0 is The calculated radius of the pipeline (mm), which is the distance from the center of the circular pipe to the center of the pipe wall, k_{mi} is the bending moment coefficient should be based on the load category, and the support angle of the soil taken should be 120°, k_{ni} the axial force coefficient should be based on the load category, and the support angle of the soil taken should be 120°, P_i is the design value of i-load acting on the pipeline (N/m).

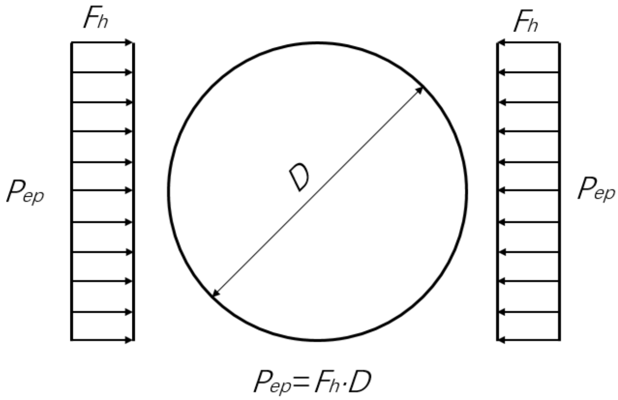

Fig. 1. Distribution model of soil lateral pressure.

4 Analysis of the influence of different soil side pressure distribution characteristics on pipeline internal forces in composite strata by load structure method

4.1 Soil lateral pressure and internal force of pipeline structure in composite formations

Assuming that the soil cover thickness of the pipeline is 6.0m, and the geological conditions at the center of the pipeline sidewall are combination I, combination II, combination III, and combination IV, the soil lateral pressure and internal force of the pipeline structure calculated according to the regulations are shown in Table 3. The backfill soil at the top of the pipeline is calculated based on the entire soil column.

Table 3. Calculation results of pipes' internal forces under different composite geo-logical combinations on the pipe side

Stratigraphic combination type	Lateral soil pressure P_{ep} (kN/m^2)	Vertical uniformly distributed load P_v (kN/m^2)	Soil weight inside the pipe cavity P_0 (kN/m^2)	Design value of maximum bending moment of pipeline (kN/m^2)	
				inside	outside
I	134.21	216	**9.27**	**32.99**	**-26.29**
II	142.67	216	9.27	31.48	-24.78
III	146.04	216	3.09	29.72	-23.19
IV	88.98	168	3.09	29.35	-23.92
V	92.16	216	12.97	41.20	-34.39
VI	96.96	216	12.97	40.35	-33.54
VII	111.36	216	6.80	36.62	-29.88
VIII	66.56	168	6.80	34.05	-28.52

From the calculation results in Table 3, it can be seen that:

(1) The smaller the water and soil pressure on the outer wall of the pipeline, the greater the internal force of the pipeline structure obtained and the higher the reliability of the designed pipeline structure. On the contrary, lower limit values may not meet the actual bearing capacity limit state or regular use state requirements.

(2) Under the same geological conditions, the lower the groundwater level, the greater the calculated internal force of the pipeline (Figure 2). In this supporting project, when the water level is at the bottom of the pipes, the bending moment on the inner side of the pipeline reaches 118.5% of that when the water level is at the top, which significantly impacts the structural design.

4.2 Sensitivity analysis of internal forces in pipeline structures to soil mechanical parameters

When conducting a detailed survey of underground engineering, the physical and mechanical properties of the soil provided in the geological survey report are a result obtained based on specific probability statistics. Due to the discrete nature of the earth on the pipe side, the mechanical parameters of the actual soil on the pipe side will continuously change near the mean of the geological survey. At this point, the actual soil lateral pressure of the pipeline may be greater than or less than the design value of the pipes.

In order to analyse the sensitivity of the jacking-pipe structure to changes in soil physical and mechanical parameters, the soil lateral pressure and internal force of the pipes were calculated by adjusting the physical and mechanical indicators of the ② sand layer in the geological survey report, as shown in Table 4, The variation pattern is shown in Figure 2.

Table 4. Calculation results of pipes' internal forces under different composite geological combinations on the pipe side

Internal friction angle of sandy soil (°)	Lateral soil pressure P_{ep} (kN/m²)	Vertical uniformly distributed load Pv (kN/m²)	Soil weight inside the pipe cavity P_0 (kN/m²)	Design value of maximum bending moment of pipeline (kN/m²)	
				inside	outside
25.0	112.21	216.0	12.98	37.62	-30.81
27.5	101.81			39.48	-32.67
30.0	92.16			41.21	-34.40
32.5	83.22			42.89	-35.99
35.0	74.92			**44.29**	**-37.48**

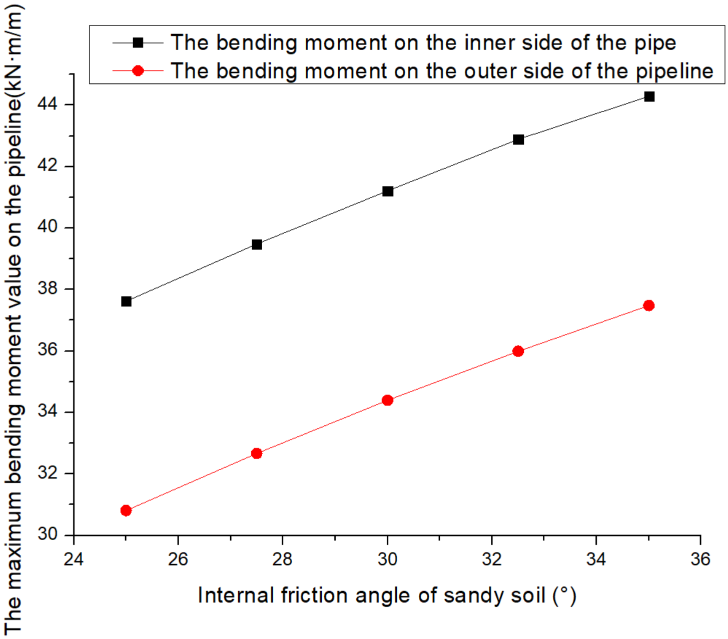

Fig. 2. The variation law of the maximum bending moment value of pipeline structure with the internal friction angle of sandy soil.

4.3 The influence of different soil lateral pressure distribution characteristics on the internal forces of pipeline structures

From Tables 3, 4, and Figure 2, it can be seen that:

(1) When the physical and mechanical parameters of the soil are lower, the calculated lateral pressure of the soil is greater, and the internal force of the pipeline is smaller, the actual reinforcement ratio of the designed pipes is smaller;

(2) When the physical and mechanical parameters of the actual buried soil layer of the pipeline are higher than those provided by geological exploration, there is a particular safety risk or usage risk in the pipe structure.

(3) When the sidewall of the pipeline is a composite formation, if the physical and mechanical indicators of the poorer shape are used to calculate the soil lateral pressure, there is a particular safety risk in the designed structure.

(4) From the perspective of safety and reliability, when using the load structure method for pipeline structure design, it is advisable to take the best possible stratum in the interval for the soil on the pipe side (with the soil load on the top of the pipe unchanged), that is, the stratum with the minor active soil pressure calculated, for calculation, which is the safest.

5 Analysis of the Influence of Different Soil Side Pressure Distribution Characteristics on Pipe Internal Forces in Composite Strata by Strata Structure Method

5.1 Basic assumptions and establishment of finite element models

To further analyze the influence of the composite layer on the structural stress of the pipeline sidewall, a 30m wide structure was established × 20m high × A 20m thick three-dimensional finite element analysis model is used to analyze the stress changes of pipeline structures under different distribution characteristics of composite soil layers. The basic assumptions of the finite element model are as follows:

(1) The soil layers on the inner and outer sides of the pipeline conform to the assumption of isotropy; The soil inside and outside the tunnel is simulated using the HSS small strain model, and the drainage type is "drainage." assume that the groundwater level is located below the pipeline, which means that the excavation of the tunnel is not affected by water pressure;

(2) The physical and mechanical parameters of the soil, in addition to the reference geological survey report, also refer to the HSS empirical parameters in relevant engineering [12]. The geological parameters used for analysis are detailed in Table 5;

(3) The filling thickness in the composite soil layer outside the pipeline (relative to the elevation of the pipeline top) is -0.6m, 0.0m, 0.6m, 1.2m, 1.8m, 2.4m, and 3.0m, respectively;

(4) The top pipe tunnel is simulated using plate elements, and the soil is simulated using high-precision ten-node triangular elements, generating a total of 9351 components.

Table 5. Small strain model parameters of soil (HSS model)

Soil layer name	γ/(kN/m^3)	c/(kPa)	Φ/(°)	E_{50}^{ref} (MPa)	E_{oed}^{ref} (MPa)	E_{ur}^{ref} (MPa)	G_0^{ref}	$\gamma_{0.7}$
① Miscellaneous fill soil	15.0	5.0	15.0	2000	2000	10000	20000	10^{-4}
② Coarse sand	21.0	0	30.0	7000	7000	35000	70000	10^{-4}

5.2 Simulation of construction process and internal force variation law of pipeline structure

In order to simplify the analysis process, two construction steps were set up to simulate the construction process of the tunnel: ① the soil solidifies under its weight; ② The excavation of some ground in the tunnel and the construction of tunnel lining resulted in a 1% geological loss due to over-excavation. Figure 3 shows the stratum's deformation cloud map when the pipeline's outer side is covered with sand.

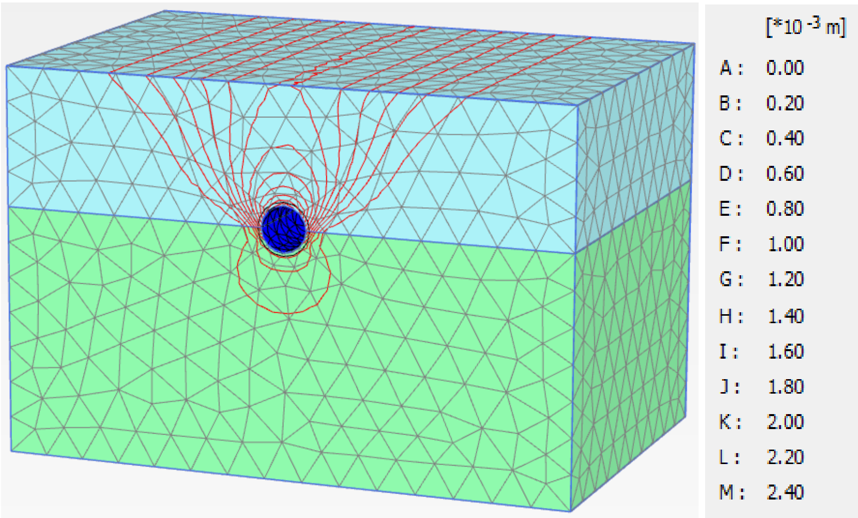

Fig. 3. Contour map of strata disturbance deformation during composite strata top pipe excavation.

Based on the results of finite element analysis, the pipe bending force values were extracted for different composite geological conditions (Table 6), from which it can be seen that:

(1) Through the three comparative analyses of Combination I, it can be concluded that using the geological structure method, the geological loss rate of pipe jacking construction has a significant impact on the internal force of the pipe structure and also has a significant effect on surface settlement. Therefore, in the actual construction process, the geological loss rate should be strictly controlled according to the design requirements to avoid various quality and safety issues caused by ground settlement caused by excessive excavation or internal force of the pipeline structure caused by absurd hole;

(2) In composite strata, the distribution pattern of different soil layers outside the pipeline has a particular impact on the internal force of the pipeline structure. Under the premise of the same formation loss rate, the deviation rate of the maximum bending moment value reaches 20%. The calculation of soil lateral pressure without considering the distribution characteristics of the stratum may have a significant deviation. In engineering design, the soil layer with the best physical and mechanical parameters should be selected along the pipeline axis to calculate soil lateral pressure reinforcement.

(3) Under the same geological loss rate, the better the physical and mechanical parameters of the soil on the pipeline sidewall, the greater the internal force generated by the pipeline structure, which is consistent with the law of load structure method.

Table 6. Calculation results of pipes' internal forces under different composite geological combinations on the pipe side

Stratigraphic combination type	Formation loss rate	Thickness of composite soil layer on the pipe side (m)		Maximum bending moment value (kN · m/m)		Maximum axial force value (kN/m)
		① Miscellaneous fill soil	① Miscellaneous fill soil	inside	outside	
I	1.0%	3.0	-0.6	-79.90	-94.48	-124.7
	1.0%	2.4	0.0	-66.82	-94.33	-130.7
	1.0%	1.8	0.6	-74.68	-94.57	-115.3
	1.0%			-69.19	-100.2	-125.8
	0.5%			-27.08	-56.89	-131.2
	0.3%			-10.35	**-39.54**	-134.7
	0.0%			13.47	-12.58	-147.7
V	1.0%	0.6	1.8	-68.73	-100.5	-119.8
	1.0%	0.0	2.4	-58.38	-104.3	-153.8
	1.0%	-0.6	3.0	-68.86	-103.7	-142.1
	0.0%	-0.6	3.0	15.29	-15.01	-179.5

6 Conclusions

Starting from the difference between large-diameter pipe jacking and existing municipal pipe network pipe jacking engineering, based on the actual engineering conditions of DN2000 pipe jacking for a 110kV transmission line in Shanxi Province, the force variation law of pipeline structures with different composite soil layer distribution characteristics on the pipeline side was analyzed through load structure method and strata structure method, and the following conclusions were drawn:

(1) The better the physical and mechanical parameters of the soil outside the pipeline, the smaller the calculated active soil pressure on the pipeline side. Under the same vertical load, the maximum bending moment of the control section of the pipeline structure is achieved. When the pipeline side wall is located in a composite formation, the section with better geological parameters should be selected as the control design section;

(2) The load structure method recommended by the regulations is adopted for design. When the groundwater level changes within the elevation range of the top and bottom of the pipeline, the maximum internal force of the pipes is calculated at the low water level, which is the control condition for internal force calculation of the pipe under corresponding conditions. At this time, the groundwater level can be taken to the bottom position of the pipe;

(3) The fluctuation of water levels has a particular impact on the internal force of the pipeline. After the completion of pipe jacking construction, it is necessary to avoid extracting a large amount of groundwater from the surrounding construction area;

(4) The load structure method design cannot reflect the impact of geological losses on the internal forces of pipeline structures during the top pipe excavation construction process. When constructing geological formations similar to background engineering, special attention should be paid to avoiding excessive holes and controlling the geological loss rate within the allowable range of the design.

Acknowledgments

This work was financially supported by the China Energy Engineering Group Shanxi Electric Power Engineering CO., LED. through Grant No. 14-K2022-16-T02.

References

1. DL/T 5484-2013, Code for design of power cables tunnel[S].
2. CECS 246:2008, Technical specification for pipe jacking of water supply and sewerage engineering[S].
3. Chen Xiaoxiang, He Lei, Sun Qing et.al (2021) A Jacking Force Estimating Formula for Precast Concrete Pipe Jacking with a Mult-curve Trajectory by Static Equilibrium Method, *Chinese Journal of Underground Space and Engineering*, 2021,17(03):800-807.
4. Li Jibo, Huang Yesheng and Zhang Xiaoying (2022) General section design of Beijing electric power rectangular pipe jacking, *SHANXI ARCHITECTURE*, 2022,48(24):155-157.
5. Ma P, Huang S, Ma B, et al. Transition of the pipe jacking technology in Japan and investigation of its application status[J]. Tunnelling and underground space technology, 2023.
6. GB/T 51358-2019, Urban underground space planning standards [S].
7. Fang-Le Peng, Yong-Kang Qiao, Jing-Wei Zhao, et al. "Planning and implementation of underground space in Chinese central business district (CBD): A case of Shanghai Hongqiao CBD." Tunnelling and Underground Space Technology, 95.
8. HUANG Zhigang, LIN Yigeng, LIU Kaixin, et.al. Research on Mechanical Characteristics of Large-diameter Straight Steel Pipe Jacking Around the Pipe, Structural Engineers, 2023,39(02):38-45.
9. Yuan Li, wang Zhijin and Sha Huanling, Analysis on the Influence of Groundwater to the Internal Force Calculation of the Pipe Jacking Structure[J]. Special Structures, 2022,39(1):64-70.
10. YANG Xian, XIAO Yu-feng, LI Yong-suo, et,al. Calculation method of the earth pressure for parallel pipe jacking with small spacing[J]. Chinese Journal of Engineering, 2021,43(10): 1376−1384.
11. Yuan Xin, Ma Baosong, Zhao Yangsen, et.al. Field Measurement and Analysis of Pipe Pressure during Box Jacking Construction[J]. *Chinese Journal of Underground Space and Engineering*, 2021,17(04):1225-1233.
12. CHEN Yun, LUO Min-min, XIA Neng-wu3, et al. Statistical analysis of existing test results of HSS model parameters for soft soils[J]. *Chinese Journal of Geotechnical Engineering*, 2021,43(supp.1):197-201.