Research and Numerical Simulation Analysis of Deformation Control for Oil and Gas Pipelines Passing through Box Culverts

Tong Wang[1,*] and Dongyang Geng[1,2,3]

[1]Hebei GEO University, No. 136 East Huai'an Road, Shijiazhuang, 050031, China
[2]Hebei GEO University, Hebei Province Underground Artificial Environment Smart Development and Management Technology Innovation Center, No. 136 East Huai'an Road, Shijiazhuang, 050031, China
[3]Tsinghua University. No. 30, Shuangqing Road, Beijing.100084, China
[*]Corresponding Author

Abstract: With the advancement of oil and gas pipeline construction, the passage of oil and gas pipelines through box culverts as essential transportation structures makes deformation control crucial for traffic safety and pipeline stability. This paper investigates the deformation control issues of oil and gas pipelines passing through box culverts, utilizing numerical simulation analysis to establish corresponding models and draw the following conclusions:① Rational deformation control techniques and construction protection measures are vital for the safety and stability of oil and gas pipelines passing through box culverts, including ground reinforcement and pre-processing techniques, as well as proper control of tunneling parameters and soil pressure balance.② Initial construction of underground engineering causes ground settlement, but measures taken can alleviate the initial settlement. During the pipe jacking construction phase, ground deformation intensifies, but subsequent settlements significantly reduce compared to the initial stage, indicating the effectiveness of the measures.③ Optimizing box culvert structural design, enhancing monitoring and maintenance, and implementing shock absorption measures are crucial for controlling the deformation of oil and gas pipelines passing through box culverts, ensuring the safe operation of pipelines and the stability of engineering structures. This study provides valuable references for similar projects.

Keywords: oil and gas pipelines; box culverts; deformation mechanism; numerical simulation; deformation control.

1. Introduction

With the continuous global growth in energy demand, oil and gas pipelines play a crucial role as vital energy transportation channels, connecting energy production areas to consumption regions. In order to achieve efficient and secure energy transport, oil and gas pipelines often need to cross various transportation and environmental obstacles such as roads, rivers, and railways. Oil and gas pipelines passing through box culverts have emerged as a common and effective solution, not only ensuring the safe operation of pipelines but also protecting the environment and human living areas from the impacts of pipeline transportation. However, with the increasing operational lifespan of oil and gas pipelines, as well as unforeseen natural and human factors, the deformation issues of pipelines passing through box culverts have become increasingly prominent. Deformation of the culverts may lead to uneven stress on the pipeline, causing pipeline leaks or ruptures and posing safety hazards. Moreover, it may even affect the stability and functionality of surrounding infrastructure. Therefore, conducting in-depth research on the deformation behavior of oil and gas pipelines passing through box culverts and exploring effective deformation control measures has become particularly important.

In the past, the study of deformation in oil and gas pipelines passing through box culverts mainly relied on experimental observations and empirical designs. Although these methods provided valuable experience to some extent, they were limited by the high cost of field experiments and the complexity of experimental conditions, making it challenging to comprehensively reflect the influencing mechanisms of various factors on culvert deformation. Hence, leveraging computer technology and employing numerical simulation methods to conduct in-depth research on the deformation behavior of pipelines passing through box culverts has become a hot topic and trend in the current research field. Numerical simulation methods, especially finite element methods, possess advantages such as efficiency, economy, and controllability, enabling them to accurately simulate the deformation process of complex structures and reveal stress distribution and deformation mechanisms within the structures. The use of numerical simulation methods in studying culvert deformation control allows for the comprehensive consideration of various factors, including materials, loads, and environmental impacts, providing a scientific basis for engineering design and construction [1-3].

The aim of this paper is to conduct an in-depth investigation into the deformation behavior of oil and gas pipelines passing through box culverts using numerical simulation methods. The paper analyzes the key factors influencing culvert deformation and proposes corresponding deformation control measures. Through this research, we hope to provide reliable theoretical guidance for the design, construction, and operation of oil and gas pipeline projects passing through box culverts, further ensuring the safe operation and maintaining the stability and continuity of energy supply. Simultaneously, this study will also offer experience and references for the application of numerical simulation methods in other similar engineering fields, promoting the constant advancement and innovation of engineering technology.

2. Project Overview

The Beijing Gas Tianjin Nangang LNG Emergency Reserve Project External Pipeline Project starts from the Beijing Gas Nangang Receiving Station's first station and ends at the southern end of Chengnan in Lixian Town, Daxing District, Beijing. The pipeline passes through Tianjin Binhai New Area, Jinghai District, Xiqing District, and Wuqing District, Hebei's Anci District, Yongqing County, and Guangyang District, and Beijing's Daxing District, covering a total of 8 counties and districts across three provinces and cities. The total length of the pipeline for this project is 224 km. The section from the Beijing Gas Nangang LNG Receiving Station to the Yongqing Interconnection Station has a pipe outer diameter of 1219 mm, designed pressure of 10 MPa, and uses X80M grade steel pipe. It is designed to transport 6000x10^4Nm^3/d and has a length of 182.08 km. The section from the Yongqing Interconnection Station to the Southern End of Chengnan has a pipe outer diameter of 1016 mm, designed pressure of 10 MPa, and uses X70M grade steel pipe. It is designed to transport 3600x10^4Nm^3/d and has a length of 41.92 km.

The project involves the trenchless crossing of the South-to-North Water Diversion Project's Tianjin mainline box culvert. A 50m protection zone is designated on each side of the box culvert, where any earthwork or construction activities are strictly prohibited. The starting point, located at Jianjing well, is 63m away from the box culvert's boundary, and the receiving point, located at Jianjing well, is 60m away from the box culvert's boundary. The horizontal length of the crossing is 207.4m, and the horizontal length of the pipe jacking is 153.4m. The project is classified as a large-scale crossing. Please refer to Figure 1 for the specific location.

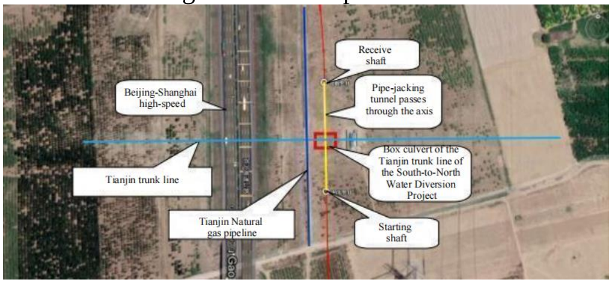

Figure 1. Schematic Diagram of the Crossing Location of the South-to-North Water Diversion Project's Tianjin Mainline

3. Box Culvert Structure and Deformation Mechanism of Oil and Gas Pipelines

3.1. Box Culvert Structure

A box culvert is a common tunnel structure that bears the dual loads of ground transportation and pipeline conveyance. During the process of oil and gas pipelines passing through box culverts, several main factors may influence them, including ground settlement, pipeline gravity, water pressure, temperature changes, and seismic effects. These factors can lead to deformation in the box culvert, subsequently affecting the safe operation of oil and gas pipelines.

3.2. Deformation Mechanism of Oil and Gas Pipelines

3.2.1 Ground Settlement

Ground settlement occurs due to factors such as the self-weight of the underground soil layers, changes in groundwater levels, artificial drainage, or mining activities, resulting in the subsidence of the ground. Ground settlement can lead to subsidence and deformation of the box culvert structure, consequently affecting the horizontal position and inclination of the pipeline.

Ground settlement may cause the following issues:

1) Culvert Subsidence: Ground settlement may cause the overall or local subsidence of the box culvert, resulting in a decrease in the height of the passageway. If settlement is uneven, it may cause imbalanced deformation in the box culvert, affecting the horizontal position and geometric shape of the passageway.

2) Pipeline Deformation and Stress: Ground settlement-induced deformation of the box culvert may impose additional stress on the oil and gas pipeline. These stresses may exceed the pipeline's load-bearing capacity, leading to deformation, fractures, or leaks in the pipeline.

3) Pipeline Inclination: Ground settlement can lead to the lowering of the pipe supports, causing the pipeline to tilt. Pipeline inclination can obstruct the smooth flow of oil and gas, impacting the normal operation and flow capacity of the pipeline [4,5].

3.2.2 Pipeline Gravity

The weight of the oil and gas pipeline itself exerts a gravitational load on the box culvert structure. For box culverts spanning larger distances, the gravity of the pipeline significantly affects its deformation. The pipeline's gravity leads to an uneven distribution of forces in the lower part of the box culvert, resulting in deformation of the structure.

Pipeline gravity's impact on the box culvert includes:

1) Uneven Force Distribution: The pipeline's gravity leads to an uneven distribution of forces in the lower part of the box culvert. The bottom part of the box culvert bears greater pressure, while the top part bears relatively lesser pressure. This uneven force distribution may cause deformation, resulting in concave or convex deformations in the box culvert.

2) Pipeline Displacement: The pipeline's gravity may cause a certain degree of settling. This will affect the horizontal position and height of the oil and gas pipeline, subsequently influencing the flow and transportation efficiency of oil and gas.

3) Pipeline Support: The support structure of the box culvert bears the gravitational load of the pipeline and thus requires proper design and reinforcement. The impact of pipeline gravity on the support structure needs to be thoroughly considered during the design phase to ensure its stability and safety.

3.2.3 Water Pressure

Underlying groundwater or surface water may exist beneath the oil and gas pipeline, subjecting the box culvert to certain water pressure. Particularly when crossing water bodies like rivers or lakes, water pressure can exert vertical and horizontal compression forces on the box culvert, leading to deformation and pipeline displacement.

The influence of water pressure on the box culvert and oil and gas pipeline includes:

1) Culvert Deformation: Water pressure exerts compression forces on the box culvert, leading to certain deformations. Especially when crossing water bodies like rivers, the bottom of the box culvert experiences vertical pressure from groundwater or surface water, potentially causing subsidence or deformation at the bottom.

2) Pipeline Displacement: Due to water pressure, the oil and gas pipeline inside the box culvert may experience some displacement. This will impact the horizontal position and height of the pipeline, potentially causing deviations and distortions.

3) Pipeline Stability: Water pressure also plays a crucial role in the support and stability of the oil and gas pipeline. Particularly during water crossing, water pressure may impose additional loads on the pipeline's supporting structure, requiring enhanced design for pipeline support.

In the engineering design of oil and gas pipelines passing through box culverts, it is crucial to consider the influence of the aforementioned factors on the box culvert structure and pipeline. Rational ground treatment and reinforcement measures can reduce the impact of ground settlement on the box culvert. The stability analysis and design of pipeline support structures should be conducted to address the challenges of pipeline gravity and water pressure. Furthermore, the effects of temperature changes and seismic actions on the structure should be considered during the design of both the box culvert and the oil and gas pipeline, ensuring their safe operation under various loads and environmental conditions. During the construction process, strict monitoring and control of the deformation of the box culvert and pipeline are necessary, along with timely implementation of necessary maintenance and repair measures to ensure the safety and stable operation of the oil and gas pipeline [6-8].

4. Numerical Model Establishment

By establishing a three-dimensional numerical model, the coupling effects between the strata, jacked tunnel, and box culvert structure during the trenchless crossing of the South-to-North Water Diversion Project box culvert are fully considered to obtain the deformation law of the strata and box culvert structure during the construction process.

4.1. Establishment of the Numerical Model

Before conducting three-dimensional numerical simulation of the trenchless crossing of the South-to-North Water Diversion Project box culvert using the jacking method, it is essential to ensure the establishment of a realistic and reliable numerical model. This involves detailed collection and analysis of geological exploration data in the project area, including geological lithology, stratum thickness, soil parameters, groundwater level, and other factors.

1) Model Dimensions: The model size of the site is 300 meters wide, with a stratum thickness of 81 meters and a depth of 80 meters, comprising a total of 32,187 elements and 18,265 nodes, meeting the size requirements to eliminate model boundary effects.

2) Stratum Division: From top to bottom, the strata are divided into silt with a thickness of 3 meters, clay layer with a thickness of 4 meters, silty clay layer with a thickness of 13 meters, clay layer with a thickness of 8 meters, silt with a thickness of 3 meters, and silty clay layer with a thickness of 50 meters.

3) Boundary Conditions: Fixed constraints are applied in the X-Z direction at the bottom boundary of the model, and horizontal constraints are applied to all other boundaries.

4) The overall model is affected by its self-weight load.

5) The soil excavation of vertical wells and the jacked tunnel are accomplished by activating and deactivating elements.

6) The overall model is affected by the groundwater level.

7) The model considers initial stress conditions and undergoes simplified calculations.

The schematic diagram of the grid division of this model is shown in Figure 2 below:

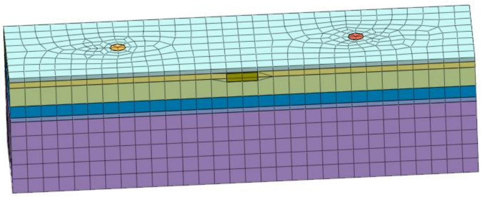

Figure 2. Schematic Diagram of Model Grid Division

4.2. Material Mechanical Constants of Strata and Box Culvert

In the numerical model, it is essential to accurately describe the physical and mechanical properties of the strata and box culvert materials. This includes various parameters of different strata, such as elastic modulus, Poisson's ratio, shear strength, etc., as well as attributes of the box culvert structure materials, such as strength, stiffness, etc. Based on geological exploration data and experimental test results, material properties are set to simulate the response of the strata and box culvert during the jacking excavation process. The physical constants used for the model's strata and materials are presented in Table 1 below:

Table 1. Strata and Material Parameters Table

Material Name	**Thickness h (m)**	**Elastic Modulus E0 (MPa)**	**Poisson's Ratiou**	**Unit Weight (KN/m3)**	**Cohesion C (KPa)**	**Friction Angleφ (°)**
Silt	3	8.52	0.3	17.2	8	29.9
Clay	4	4.47	0.3	18.2	20.3	12.6
Silty Clay	13	4.81	0.3	18.5	14.3	12.8
Silt	8	5.19	0.3	19.7	19.9	13
Clay	3	10.22	0.3	19.9	7.3	31.1
Silty Clay	50	4.57	0.3	19.7	17.2	21.8
Reinforced Concrete	-	30	0.3	23.52	-	-

5. Calculation Results Analysis

5.1. Settlement of Strata before Precipitation

The settlement of strata before precipitation was analyzed, as shown in Figure 3 to Figure 5:

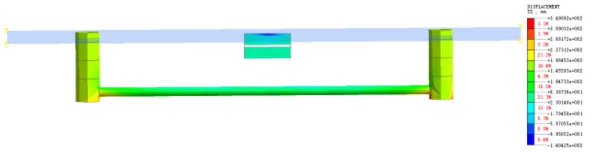

Figure 3. Settlement settlement of final construction

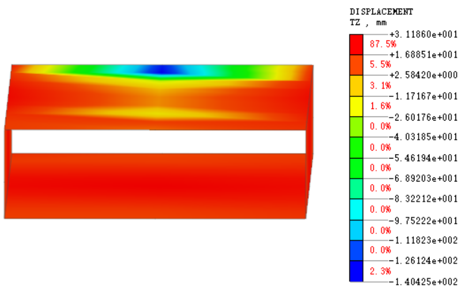

Figure 4. Settlement settlement of final construction of box culvert

Figure 5. Final settlement cloud map of the formation

Based on the provided data, the settlement analysis shows the following results:

The settlement of the vertical wells reached 350mm. The significant settlement of the vertical wells may be attributed to the construction methods used and the geological characteristics of the strata. Proper planning, design, and support measures are essential during the construction of vertical wells to ensure their stability and safety.

The settlement of the box culvert was 31.18mm. The relatively small settlement of the box culvert indicates successful design and construction, ensuring its stability during the jacking excavation process. The box culvert plays a crucial role in providing a stable passage for the oil and gas pipeline, contributing to its safe and smooth operation.

The settlement of the strata was 552mm. The strata experienced significant deformation during the jacking excavation process. To mitigate the adverse effects of settlement, it is vital to evaluate and control the strata's deformation. A comprehensive monitoring system, real-time response, and optimization of the design can aid in minimizing the impact of settlement on the construction.

To reduce the impact of settlement on the project, several measures can be implemented:

1) Construction monitoring and real-time response: Establish a comprehensive settlement monitoring system to continuously monitor settlement during underground construction. By promptly detecting settlement issues, project managers and technical personnel can respond in a timely manner to ensure construction safety and stability.

2) Settlement prediction and optimization of design: Predict settlement during the design phase using modern numerical simulation and analysis methods. Based on the predicted results and considering strata characteristics and engineering requirements, optimize the design. This optimization may involve selecting appropriate construction methods, implementing strata reinforcement measures, and setting reasonable construction schedules and safety margins.

3) Strata reinforcement and support measures: For strata with significant settlement impact, implement suitable reinforcement and support measures to enhance stability and load-bearing capacity. Common strata reinforcement measures include soil stabilization, grouting consolidation, steel supports, and rock anchoring. Reinforcing the strata can reduce settlement's impact on underground structures and surface buildings.

5.2. Stratum settlement before precipitation

To ensure that ground settlement does not affect the construction of vertical wells, a series of measures have been taken to reduce construction risks. Larson IV-type steel sheet piles, each 12m in length, have been installed between the vertical wells and the boundary of the South-to-North Water Diversion Project protected area to prevent surface settlement within the protected area. These measures are crucial for the overall stability and safety of the project.

In the construction model, detailed simulations of the main processes were carried out, using the same simulation methods, constitutive relationships, and assumptions to maintain consistency with other construction methods. For the installation of steel sheet piles, the model carefully considered their geometric dimensions, material properties, and loading conditions to ensure that the steel sheet piles effectively support the vertical well construction.

Box culvert, shaft and formation settlement as shown in Figure 6-8:

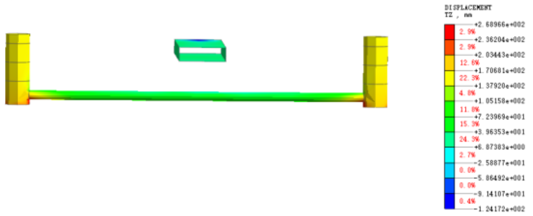

Figure 6. Cloud settlement of shaft final construction

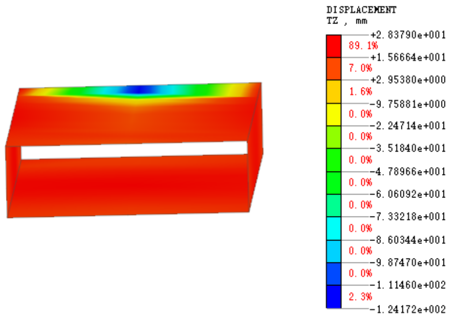

Figure 7. Cloud settlement of final construction of box culvert

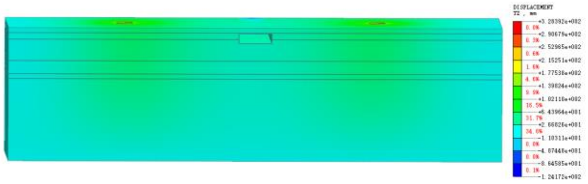

Figure 8. Final settlement cloud map of the formation

Based on the above-mentioned diagrams, the settlement of the vertical wells is 220mm, the final settlement of the box culvert is 28.3mm, and the final settlement of the ground is 328mm. It is evident from the data that settlement has been reduced. This indicates that during the underground construction process, despite the ground experiencing some recompaction and compression, the settlement impact has been alleviated to some extent through appropriate measures.

This signifies that the installation of steel sheet piles during the construction of vertical wells has played a significant role, effectively preventing ground settlement from affecting the surface within the protected area of the South-to-North Water Diversion Project. By setting up steel sheet piles, lateral displacement of the underground soil has been successfully limited, effectively controlling the settlement of the vertical wells, box culvert, and ground. This is crucial for the safety of buildings, infrastructure, and underground pipelines within the protected area. Reducing ground settlement can prevent adverse phenomena such as surface collapse and ground cracks, ensuring the safety and stability of the surrounding area. At the same time, steel sheet piles, as robust temporary support structures, enhance the stability of the soil, providing reliable support for the construction of vertical wells. They can withstand significant soil and water pressure, maintaining the stability of the construction site while improving construction efficiency.

In addition to the installation of steel sheet piles, comprehensive construction management and monitoring are also necessary during the construction process. Real-time monitoring of construction progress and settlement data allows for timely detection of issues and adjustments as needed. Strengthening communication and cooperation among the construction team ensures the effective implementation of construction processes and support measures. Such comprehensive measures can maximize the stability and safety of the project, ensuring smooth construction without adverse effects on the surrounding environment and facilities.

6. Deformation Control Research and Corresponding Measures

In order to effectively control the deformation of the oil and gas pipeline passing under the culvert, this paper proposes the following recommendations: optimize the culvert structure design to increase its bearing capacity; strengthen the monitoring and maintenance of the culvert to promptly identify and address issues; implement seismic mitigation measures to reduce the impact of earthquakes on the structure. The following are some specific measures:

6.1. Optimize Culvert Structure Design

During the design phase, the culvert structure can be optimized to increase its bearing capacity to withstand the gravity and water pressure exerted by the oil and gas pipeline. Utilize stronger and more durable materials, appropriately increase the wall thickness and supporting structure of the culvert to enhance its overall strength and rigidity. Additionally, based on the specific engineering conditions and geological factors, choose the appropriate shape and size of the culvert to enhance its resistance to subsidence and deformation.

6.2. Strengthen Monitoring and Maintenance of the Culvert

Regular monitoring of the culvert structure after construction is crucial. Establish a robust monitoring system that includes subsidence observation, displacement monitoring, stress measurement, etc., to promptly detect any deformation of the culvert. Once the subsidence exceeds the predetermined threshold or other anomalies are observed, immediate maintenance and remedial measures must be taken. Timely repairs to damaged sections of the culvert ensure its normal operation and service life.

6.3. Implement Seismic Mitigation Measures

Earthquakes are one of the significant factors causing deformation in underground structures. To mitigate the impact of earthquakes on the culvert structure, seismic mitigation measures can be employed. One common approach is to install seismic dampers at the bottom or sides of the culvert, such as seismic rubber pads or damping steel plates. These dampers can absorb seismic energy, reducing the impact force on the structure and consequently minimizing the culvert's deformation.

By optimizing the culvert structure design, strengthening monitoring and maintenance, and implementing seismic mitigation measures, the deformation of the oil and gas pipeline passing under the culvert can be effectively controlled, ensuring the safe and stable operation of the project. These measures not only safeguard the secure transmission of oil and gas through the pipeline but also protect the integrity of the culvert structure and ensure the safety of the surrounding environment and buildings. Additionally, continuous accumulation of practical experience and further research is necessary to improve the construction quality and deformation control level of the oil and gas pipeline passing under the culvert project.

7. Conclusion

Through the research and numerical simulation analysis of the oil and gas pipeline, we draw a series of important conclusions:

In the engineering design and construction of the box culvert under the oil and gas pipeline, reasonable deformation control technology and construction protection measures are crucial to ensure the safety and stability of the project. By adopting the formation reinforcement and pretreatment technology, the geological conditions can be improved and the risk of formation deformation can be reduced. At the same time, reasonable control of tunneling parameters and soil pressure balance, as well as setting the supporting structure, are the key measures to effectively reduce the deformation of the formation and box culvert.

In the initial construction stage of underground engineering, the stratum is affected by rearrange and compression, leading to settlement phenomenon. By taking corresponding measures, including reasonable construction methods, the initial settlement level was successfully reduced and made it lower. However, in the subsequent pipe jacking construction stage, the increase of construction activities leads to further aggravation of formation deformation, resulting in a significant increase in settlement. Nonetheless, it is noteworthy that the settlement of subsequent stages is still significantly reduced compared to the initial sedimentation level. This fully proves that the stratigraphic control measures and reinforcement measures have achieved significant results in the subsequent construction process and successfully reduced the impact of formation deformation.

By optimizing the structure design of the box culvert, strengthening the monitoring and maintenance, and taking shock absorption measures, it plays an important role in effectively controlling the deformation of the box culvert under the oil and gas pipeline. These measures can help to ensure the safe operation of the oil and gas pipelines and the stability of the engineering structure.

Acknowledgement

Research on the protection of oil and gas pipeline under the south-to-north water transfer water tank culvert

Fund number: 2022-66

References

[1] Pang Yuanzhi. Design of china-Myanmar oil and gas pipeline crossing railway protection engineering. Railway Construction Technology, 2014, No.250 (10): 82-84.

[2] Zhang Yu, Liang Hao, Lin Liang, et al. Experimental study on the mechanical response of buried pipelines under different settlement modes. Rock-soil mechanics, 2023,44(06):1645-1656.DOI:10.16285/j.rsm.2022. 0983.

[3] Liu Zongqi. Study on settlement monitoring and risk control of oil and gas pipelines. China University of Petroleum (Beijing), 2019.DOI:10.27643/d.cnki.gsybu. 2019.001434.

[4] Zhu Junkai, Cao Xingbin, Fang Linjian, etc. Stress analysis of foundation settlement pipelines in oil and gas station field based on ABAQUS software. Corrosion and Protection, 2018, 39 (11): 878-882 + 887.

[5] Xiu Lianke, Zhang Wenbin. Buried oil and gas pipelines are affected under several special geological conditions. Chemical Engineering and Equipment, 2018, No.256(05):104-105+121.DOI:10.19566/j.cnki.cn35-1285/tq. 2018.05. 037.

[6] Wang Guowei, Gu Shiguo, Liu Lin, etc. Study on the technical evaluation of horizontal directional drilling of oil and gas transportation pipeline. Subgrade works, 2021, No.217(04):169-172.DOI:10.13379/j.issn.1003-8825.202006038.

[7] Zheng Shuangying, Yang Lizhong. Study on the dynamic response law of buried gas transmission pipeline under the seismic action of underpass tunnel blasting. Blasting, 2015, 32 (04): 69-76 + 109.

[8] Guo Zhihong, Tang Yu, Du Manchang and so on. Analysis on the impact of oil and gas pipeline through river tunnel. Environmental protection of oil and gas fields, 2023, 33 (03): 49-52 + 57.