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Study on the Impact of Different Pile Foundation Construction Methods on Neighboring Oil and Gas Pipelines under Very Small Clearances

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Abstract: With the acceleration of transportation infrastructure and the densification of transportation networks, there has been an increase in bridge pile construction near oil and gas pipelines. Selecting bridge pile construction methods with minimal impact and reducing the adverse effects of bridge pile construction on nearby oil and gas pipelines are of great importance. This paper uses FLAC3D 6.0 software to simulate and analyze the impact of two different pile construction methods, rotary drilling and impact drilling, on adjacent oil pipelines. The results show that the horizontal displacement of oil pipelines during rotary drilling construction is nearly 90% lower than that of the traditional impact drilling method, and the axial stress is reduced by nearly 85%. Furthermore, numerical simulations of rotary drilling under different conditions were conducted to analyze and summarize the patterns of how different conditions affect construction vibration and stress. This study provides a reference for bridge pile construction near oil and gas pipelines or important buildings.

Keywords: oil pipeline; pile foundation construction; construction impact control; numerical simulation

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1. Introduction

In recent years, oil and gas pipelines have become more and more important in the construction of cities and towns around the world. Especially in China, with the acceleration of urbanization, pipeline transportation has been widely used in energy transmission and municipal pipeline network systems, with a total length of more than 100,000 km of new construction and renovation each year [1,2]. Pipeline transportation has significant advantages, such as strong carrying capacity, a small footprint, low energy consumption, low cost, and goods levels of safety, reliability and continuity [3], which means that it can meet urban demand, promote economic growth and improve the quality of life of citizens. However, with the large number of highways, railroads and other infrastructure being built in China, it is inevitable that there will be situations where pipelines will run parallel to or cross existing pipelines, which are usually crossed by bridges. How to ensure the safety of oil and gas pipelines, which often span thousands of kilometers and stretch across the land in China, has become an increasingly prominent issue. In order to strengthen the protection of pipelines, the "Law of the People's Republic of China on the Protection of Oil and Gas Pipelines" came into force on 1 October 2010, which places the protection of China's oil and gas pipelines within the legal system, and provides a strong legal guarantee for the protection of oil and gas pipelines, in accordance with the law [4]. At present, the most common construction method for bridge pile foundations is percussion drilling [5], which allows for continuous construction characteristics. However, the method generates large vibrations and impact loads, and produces a certain degree of disturbance in the rock and soil layer around the oil and gas pipeline. This poses a threat to the safe and

stable operation of existing oil and gas pipelines. In the event that a historic oil and gas pipeline bursts, ruptures or leaks, the consequences are serious both from a financial and environmental standpoint. Alkhdour, A and Yasin, AA, etc. [6], optimize soil nail design for deep excavations in fast-draining soils, identifying a system with 8 m long nails at a 30-degree angle and 1.5 m spacing as effective for enhancing stability and reducing construction costs and the duration. Shirgir, S and Shamsaddinlou, A, et al. [7] present a dual-approach optimization of soil nailing systems using metaheuristic and reliability-based methods, emphasizing the impact of geometric parameters and uncertain mechanical and soil parameters on system stability and safety.

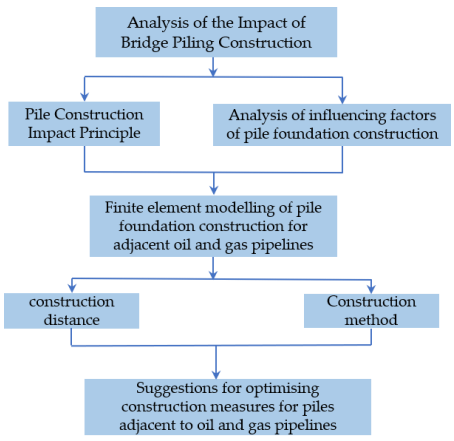
At present, the impact of blasting or non-blasting vibrations on oil and gas pipelines has been studied at home and abroad. In 1940, due to the successful development of high-power drilling rigs, drilled piles were first applied in the United States, and then rotary drilling of concrete piles was used for the first time during the construction of the foundation of the Maracaibo Bridge in Venezuela [8], in South America. With the rapid development of drilling tools, bored pile technology has been widely used around the world. In 1983, the Eighth International Conference on Soil Mechanics and Foundation Engineering organized by the former Soviet Union was held in Moscow, in which engineers representing Britain, France and Germany discussed the development of bored piles at the time, and mainly explored the settlement of pile foundations, drilling equipment and the improvement of bearing capacity [9]. In 1996, Luo Jun Jia [10] studied the phenomenon of reaming during the construction of piles. Reaming generally occurs when the groundwater is fluid, the drilling cone oscillates and floats, and the indigenous layer is loose, etc., and if several of these conditions are serious, it will easily lead to the occurrence of the hole collapse phenomenon. If the depth of the drilling hole meets the design and construction requirements, there is no need to expand the hole. However, if the phenomenon of collapse occurs, the amount of the concrete injected must be increased to ensure the quality of the pile foundation hole. Finally, if the hole wall continues to collapse, it will be handled according to a collapse accident. In 2004, Poulos [11] conducted a study on pit construction, showing that the use of pit monitoring technology can, to a certain extent, ensure the safety and integrity of both the pit construction and the surrounding structures. The study confirmed that pit monitoring technology can ensure the safety of pit construction and the surrounding construction environment, and once a problem occurs, it can be detected in good time, which can effectively prevent the occurrence of construction accidents. Meanwhile, by analyzing the test results, it can provide certain reference values for the improvement and optimization of construction methods. In 2005, E.A. Sellountou and Ming-Fang Chang et al. [12] studied the loading mechanism of bored piles and adopted a method of statistics combined with a data model for the design. Reference was made to a large number of post-processing experimental data from construction sites, and they derived a method of judging the limit of super-long bored piles. Super-long bored piles are deep foundation elements, drilled into the ground to provide stable support for structures, by reaching down to stronger soil or rock layers. The method for determining the limits of super-long bored piles, along with advanced test methods for conducting large tonnage pile foundation load tests, has been validated through engineering examples. Following this, countries began to conduct in-depth research on drilled pile-forming machinery, tailoring their research to fit their unique topographical needs with appropriate hole-forming machinery and construction methods. Due to the early development of mechanization abroad, drilling machinery has progressed towards the development of and research on new types, including intelligent systems and new materials.

Research in this area started relatively late in China. Yao Zhiwei [13] conducted a study on the stability of a borehole wall under the effect of mud shielding. The authors found that the greater the specific gravity of the mud in the borehole, the better the stability of the borehole wall, which ensures the quality of the pile foundation's borehole formation. A study by Xu Fang Qin and Wang xiao [14] in the Chongqing high-fill area found that rotary drilling rigs were recommended for the construction of piles due to the inability to

retain mud in the holes of percussive and rotary drilling rigs because of the low water table, which resulted in the inability to form an effective mud shield, affecting the quality of the holes and increasing the risk of hole collapse and burial of the drilling rigs. Pingyi Wang and Maozhong Tian [15] studied the mechanical hole formation process in a deep backfilled, strong karst area and found that construction in this area is prone to hole collapse, so it is recommended to use the full steel shroud follow-up method in order to prevent the hole collapse problem. Pan Xianyi, Liu Yaofeng and Liu Hang, et al. [16] studied the force on reinforcing cages in filled piles, and pointed out that the quality of the concrete, filling speed, geological conditions and human factors are the main reasons for the uplift of reinforcing cages, and suggested that the quality of the concrete and mud, the filling speed, and the speed of raising the conduit, etc., should be strictly controlled to prevent the problem. The technology used for cast-in-place piles has seen significant developments over the years and has reached maturity. With the proliferation of pile foundation construction, instances of such construction near important buildings or equipment have increased, prompting a newfound focus on the study of their impact on adjacent, important buildings or infrastructure. Qiu Qiong [17] employed numerical simulation software Midas v2021 to develop a model on the interaction between tunnels and buildings. This simulation analyzed different deformations of the building's pile foundations at various tunnel sections and during different excavation stages, namely before, during and after. It identified locations experiencing significant bending moments, thereby forecasting construction impacts, and signaling potential risks. Through theoretical calculations and numerical simulations, Li Bin [18] investigated the effects of bridge pile construction on both the longitudinal and transverse deformations of existing subway tunnels, as well as on the performance of the tunnel lining.

In conclusion, the construction technique for bored piles has reached a near-mature stage through extensive development and has become a popular research subject regarding its impact on construction. Nonetheless, the bulk of the prevailing research is concentrated on the inherent collapse risk associated with the pile hole or its effects on adjacent, vital buildings; research on minimal clearance beneath adjacent oil and gas pipelines has received relatively less attention. Owing to the complexity of construction processes, oil and gas pipeline leakages during construction, leading to human casualties and financial losses, are prone to occur. Under these circumstances, enhancing further research on control technologies related to drilling construction impacts becomes increasingly essential. This paper begins with a study of existing engineering cases, employs numerical simulations to investigate the effect of rotary drilling over conventional impact drilling on the impact to surrounding soils, and examines the influence of various factors on construction-induced vibrations and stress, aiming to establish patterns. This could expedite construction progress, to a certain extent, and ensure construction safety, offering crucial guidance for similar engineering projects.

Here is a brief roadmap (Scheme 1).



Scheme 1. Brief roadmap.

2. Materials and Methods

2.1. Project Overview

This paper focuses on the Guangxi G72 Quannan Expressway Guiliu Reconstruction and Expansion Project. The project concerns the Wengcun No. 1 Bridge, main bridge right line pier 6#, and the oil pipeline that is only 6 m apart. This paper focuses on the bridge pile construction for the oil pipeline impact simulation, as well as the safety control of the key technology for research progress elaboration. The bridge and the oil and gas pipeline location on the plan and the left line of the main bridge-type arrangement are shown in Figures 1 and 2.

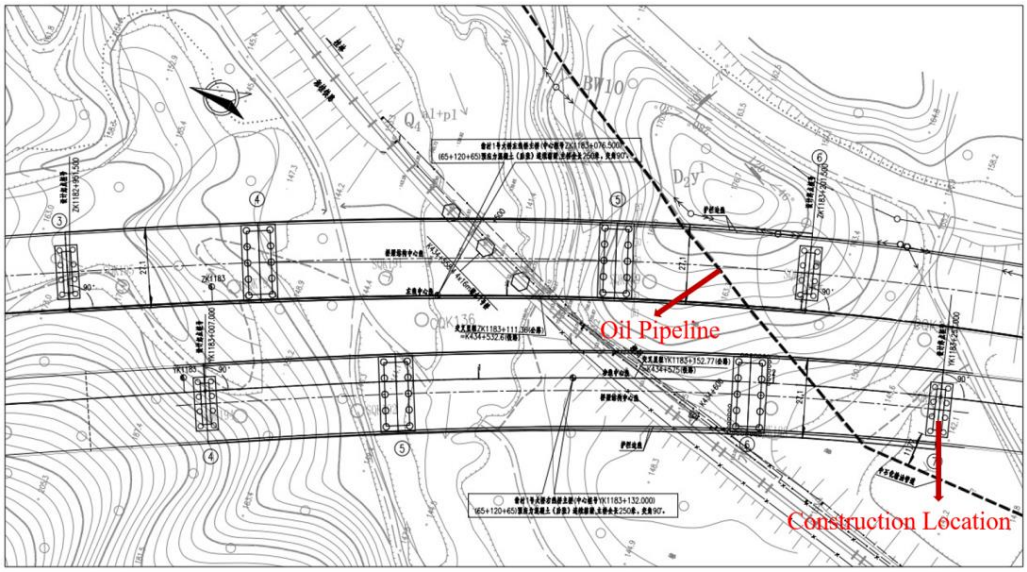


Figure 1. Plan view of the main bridge of Wengcun No. 1 Bridge.

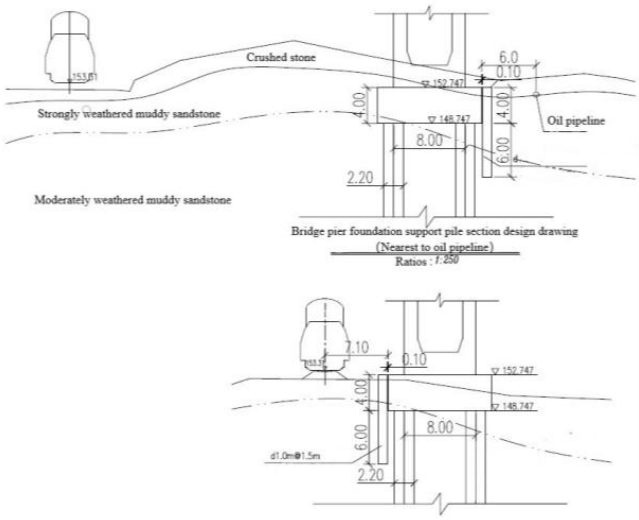


Figure 2. Wengcun No. 1 Bridge, left lane bridge layout plan.

The main research object of this paper is the pile foundation construction of pier 6# in the right line of the main bridge, which is only 6 m away from the oil transportation pipeline, and the construction is located in the mid-level, which is difficult to construct and is high risk and has high research value. For the subsequent numerical collection of the relevant information, the materials and quantities for part of the pile foundation project are shown in Tables 1 and 2.

Table 1. Quantity table for pile work for the main bridge of Wengcun No. 1 Bridge.

Piers		Root Number	Φ1.8 m Single Pile Length (m)	Root Number	Φ2.2 m Single Pile Length (m)
Left lane of Wengcun No. 1 Bridge	3#	8	24		
	4#			10	39
	5#			10	46
	6#	8	24		
Right lane of Wengcun No. 1 Bridge	4#	8	33		
	5#			10	39
	6#			10	39
	7#	8	20		
Total		32		40	

Table 2. Quantity table for pile work materials for the main bridge of Wengcun No. 1 Bridge.

Piers		HRB400 Steel Reinforcing Bar			HPB300 Steel Reinforcing Bar	C30 Concrete	Φ57 × 3 mm Sonotube
		Φ28 (kg)	Φ25 (kg)	Φ16 (kg)	Φ10 (kg)	(m^3)	(m)
Left lane of Wengcun No. 1 Bridge	3#	26,852.65	1892.15	254.7	4587.2	492	800
	4#	65,464.7	4909.6	530.9	10,482	1488.2	1600
	5#	76,090.7	5646	610.5	11,872.8	1754.3	1880
	6#	26,852.65	1892.15	254.7	4587.2	492	800
Right lane of Wengcun No. 1 Bridge	4#	36,589.9	2680.6	361	5738.6	674.9	1088
	5#	130,929.3	9819.2	1061.8	20,964.1	2976.4	3200
	6#	130,929.3	9819.2	1061.8	20,964.1	2976.4	3200
	7#	22,679.5	1576.8	212.4	4075.5	410.2	672
Total		516,388.7	38,235.7	4347.8	83,271.5	11,264.4	13,240

2.2. Theoretical Analysis of the Role of Pile Excavation on the Influence of Pipelines

The analysis of the impact of pile foundation construction of the Wengcun No. 1 Bridge bearing platform on the oil pipeline concerns the analysis of the impact of pile foundation hole excavation on the surrounding environment. This includes assessing whether the stress released during excavation causes stress concentration on the oil pipeline, pipeline deformation due to displacement and cracking. However, this analysis does not take into consideration the stability of the pile foundation itself during the excavation process, nor does it consider the role of the surrounding soil in supporting the pile foundation during excavation. In the process of pile foundation excavation, with the removal of the excavated soil body during the process of hole formation, the stress of the original soil body is released, and the stress field belonging to the soil itself changes accordingly. Displacement deformation of the pile foundation structure and the settlement of the surrounding soil body are all deformations generated in the process of pile foundation hole formation and excavation. As the pile foundation excavation process proceeds, the pile foundation structure increases with the displacement of the excavated soil body, and the soil body around the pile foundation settles immediately afterwards. The settlement of the surrounding soil will affect the buildings and buried pipelines around the pile foundation.

2.2.1. Soil Deformation Outside the Pile Excavation Hole and Influencing Factors

With the removal of the soil inside the pile foundation during pile excavation, the surrounding structure is displaced toward the center of the pile foundation, which leads to the displacement of the soil outside the pile foundation in a horizontal direction. Therefore, the horizontal stress in the soil outside the pile foundation structure decreases, and the corresponding shear force in the vertical direction increases, resulting in the appearance of a plastic region in the soil above the pile foundation. Relative to the deformation of the upper enclosure structure and the soil body of the pile foundation, the lower soil body in

the excavation surface inside the pile foundation produces horizontal displacement under the action of excavation. Furthermore, concerning the lower soil body under the action of excavation, the horizontal stresses and vertical shear increase accordingly, resulting in a localized plastic zone in the area of the lower passive soil body of the pile foundation. When the pile foundation is set in a soil layer with poor soil quality, in the excavation process, as a result of the surrounding displacement and deformation and the joint action of the outer soil body and the lower soil body, the outer soil body of the pile foundation will slide to the inner side of the hole during the excavation process, resulting in the settlement of the outer soil body during the excavation process of the pile foundation.

2.2.2. Deformation and Damage Mechanism of the Pipeline

The main reason for the deformation of the pipeline during pile foundation hole formation is due to the excavation of the soil inside the hole. With the excavation of the soil inside the pile foundation, the balance of internal forces on the soil of the side wall of the pile foundation is broken, i.e., the soil around the pile foundation is removed by the soil pressure due to the unloading of the soil inside the pit during the excavation process, which breaks the balance of stresses and leads to a change in the forces on the soil of the side wall of the pile foundation. Therefore, according to deformation theory of elastic mechanics, assuming that the principal stress exerted by the excavated soil inside the pile foundation on the pile foundation enclosure structure before excavation is σ_2, then the initial strain on the soil body of the side wall of the pile foundation in the direction of the pile foundation excavation is ε_2:

$$\epsilon_2 = 1/E\,[\sigma_2 - \mu(\sigma_1 - \sigma_3)], \tag{1}$$

where E is the modulus of elasticity of the pile excavation soil; μ is Poisson's ratio on the pile excavation soil; σ_1, σ_2, σ_3 are the principal stresses on the pile excavation soil in three directions.

With the excavation of the pile foundation, the principal stress σ_2 on the soil body of the side wall of the pile foundation becomes 0. Because the stress balance is broken, the soil body of the side wall of the pile foundation is bound to be deformed and displaced with the excavation of the pile foundation. Because the pipeline is located in the outer soil body of the pile foundation, due to the pipe–soil interaction, the displacement of the soil body of the side wall of the pile foundation will inevitably lead to the displacement and deformation of the surrounding buried pipeline. In the process of pile foundation excavation, due to the stress released by the soil inside the pile foundation, resulting in the displacement of the soil on the side wall of the pile foundation, thus because of inter-soil stress concerning the soil around the pipeline settlement will also occur. When the soil settlement around the pipeline and the pipeline settlement difference is large, the corresponding stress that the pipeline is subjected to will also change; when the stress generated by this settlement is greater than the pipeline's bearing capacity, the pipeline will be damaged. As the analyzed oil pipeline is part of a rigid buried pipeline, the authors believe that if damage occurs, the main cause of damage will be due to the fact that the pipeline is subjected to excessive stress in the longitudinal direction, resulting in a fracture in the pipeline cross-section, or the joints of the pipeline may not be able to bear the pressure, which would lead to the leakage of the pipeline, and the pipeline would be cracked in the radial direction under the action of such stress.

2.2.3. Oil Pipeline Safety Control Standards

The pipeline damage caused by pile excavation can be discerned by the allowable stress (allowable strain) of the pipe joints, or the maximum allowable turning angle at the joints. Referring to "Oil and Gas Pipeline Safety Regulations" SY 6186-2007 [19] and "Oil and Gas Pipeline System Security Risk Levels and Safety Preventive Requirements" GA 1166-2014 [20], this simulation takes the permissible pressure (10 MPa) designed for the oil pipeline of Guangxi Oil Transmission Department No. 2 of the South China Branch of the National Pipe Network Company (NPNC) as the safety control standard.

3. Numerical Simulations

3.1. Model Building

Vibration control related to the pile foundation construction immediately adjacent to the oil transportation pipeline [21] is the key problem studied in this paper. A two-dimensional numerical model is established, according to the location of pier No. 6 of the mainline left bridge of Wengcun No. 1 Bridge and the oil transportation pipeline, as shown in Figures 3 and 4. During the whole simulation process, the impact on the oil pipeline caused by the vibration from the construction of the pile foundation closest to the oil pipeline is mainly considered during the construction.

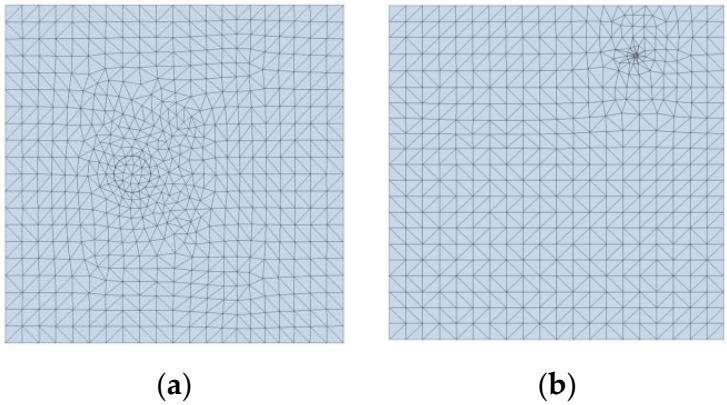


Figure 3. (**a**) Top view of model figure; (**b**) front view of model figure.

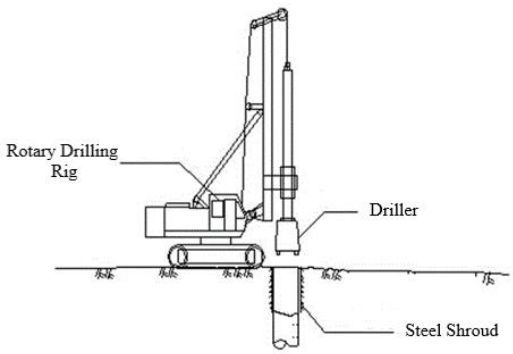


Figure 4. Schematic diagram of rotary drilling method.

In this paper, the Rhino 8.0 finite element software is used to establish the model; a cube is constructed in the software, which is then meshed and given boundary conditions, followed by some adjustments to make it more realistic and improve the accuracy of the simulations. The processed mesh file is then imported into the FLAC3D software. The pile foundation is equivalent to a cylinder, with a diameter of 1 m and a length of 10 m, and the pipeline is simplified as a steel column, with a diameter of 30 cm and a length of 20 m. The minimum distance of the pile foundation from the oil transportation pipeline is 6 m. The top view and front view of the model are shown in Figure 3.

3.2. Model Parameters

The physical parameters of the soil body are shown in Table 3, based on a comprehensive consideration of the geological survey of the site and the reference values of the relevant norms for rock–soil and structural parameters.

Table 3. Physical parameters of the soil.

Stratigraphic Name	Natural Density (kN/m^3)	Modulus of Elasticity (MPa)	Poisson's Ratio	Cohesion c (kPa)	Angle of Internal Friction θ (°)
Grit	18	6	0.49	10	20
Silty clay	17	30	0.48	20	14
Crushed or broken rock	18	86	0.47	15	24
A block of stone	20	100	0.47	20	30
Strongly weathered Muddy sandstone	24	80	0.35	18	22
Moderately weathered Muddy sandstone	24	120	0.35	30	25
Pipe	25	20,000	0.2		

3.3. Simulation Scenarios

The upper boundary is set as a free boundary to match the actual construction situation. The model is set to be vertical in the Z-axis direction, so the pile foundation model is set to be vertical in the XY-axis direction, the pipeline model is set parallel to the Y-axis, and the constraints are set in the XY-axis direction, and for the ground, the constraints are set in all three directions, and the nodes of the side boundaries are applicable to the free field conditions.

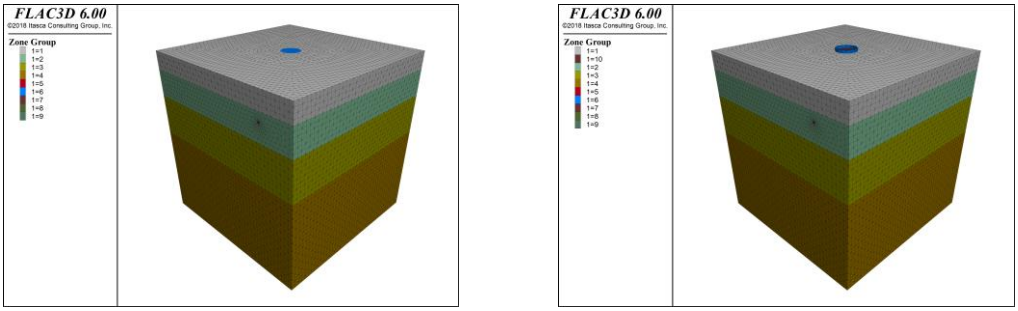
The basic assumptions for modeling are as follows:

- The pipelines are considered as equal diameter and equal wall thickness fittings, without considering the effect of the joint fittings, and the constitutive relations are considered as linear elastic materials;
- The soil is considered as a continuous linear elastomer in a porous medium and the Mohr–Coulomb damage criterion is applied (asymmetric solver is chosen);
- There are no contact surface units between the pipeline and the soil, and the two are considered to be in close contact with each other, without misalignment.

The reason for using the FLAC3D finite element simulation software in this paper is that the software is specifically designed for geotechnical engineering. It has significant advantages in dealing with complex geological conditions and deformation issues. In regard to this area of expertise, it boasts high computational efficiency, especially when handling large geological models. The downside is that it is relatively difficult to master and its application in non-geotechnical fields is limited. The Griddle processed mesh model is imported into the FLAC3D software, the structural units are grouped and assigned values, the gravity conditions and contact surface parameter conditions are given and the environment is initialized, followed by adding monitoring information. Finally, additional pile foundation loads are simulated, and the number of operations is 80,000 [22].

In an attempt to minimize the impact on oil pipelines during pile foundation construction, this paper will explore the role of rotary drilling [23] (as shown in Figure 4) in controlling construction impacts. The rotary drilling method of piling is a method of piling that is carried out using a specialized rotary drilling rig, as shown in Figure 5. The rotary drilling rig, through its power system, drives the rotation of the rotary drill rod and drill bit. The drill bit is chosen based on the design requirements and its suitability for the local geological conditions, which includes single spiral, double spiral and flat drill bits. As it rotates, the drill bit slices and fractures the soil, which is then extracted from the ground via the drill rod's rotating and lifting actions. To prevent hole collapse, the rotary method additionally employs steel casings, thereby further minimizing the vibrational impact. In contrast with the traditional impact drilling method that employs a hammer to continuously strike the ground at frequencies of 20–50 Hz, the vibrational and stress impacts induced by rotary drilling rigs are considerably lower than those produced by impact drills. Nonetheless, the rotary method has its drawbacks, such as reduced efficiency in hard or stone-containing soil layers and potential damage to the drill bit. Furthermore, when considering construction costs, rotary drilling rigs tend to be more expensive. This method involves the use of mechanical equipment with a drill bit to excavate a pile hole through rotary drilling into the ground, in which a reinforcing cage is then placed, and

concrete is poured, to form the pile foundation. The rotary drilling method of pile foundation construction is widely used in modern construction, especially in urban construction and large infrastructure projects. The rotary drilling method includes the addition of a steel shield around the pile foundation; the shield is made of 14 mm steel plate that is rolled into a shape, its inner diameter is 0.3 m larger than the designed pile diameter, the upper and lower periphery of the mouth is welded with a stiffening ring; the rotary drilling method imposes a smaller load than traditional percussion drilling of the hole [24–26]. The modeling of the traditional percussive pile and rotary drilling method is shown in Figure 5. The difference between these two models is the presence or absence of steel shoring to minimize construction impacts.



(**a**) (**b**)

Figure 5. (**a**) Conventional percussive pile model; (**b**) rotary drilling model.

4. Results and Discussion

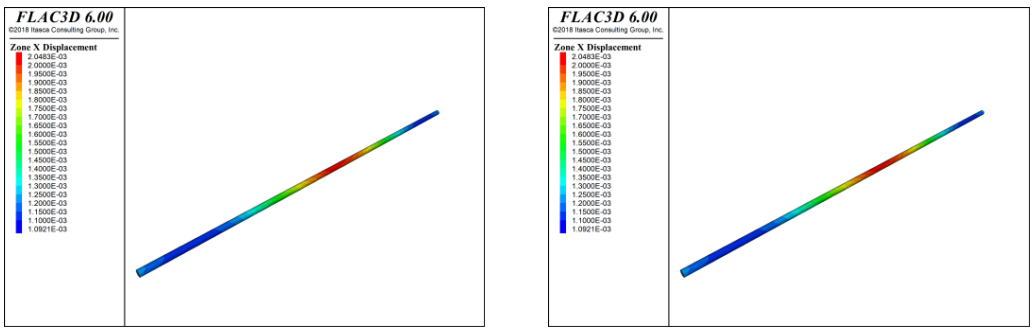
4.1. Simulation of Different Construction Methods

4.1.1. Construction Impact Displacement Analysis

In order to analyze the displacement response characteristics of the model after pile excavation, the X-direction and Z-direction displacements of the pipeline generated by the traditional percussive drilling pile excavation method and rotary drilling method are analyzed, respectively. The X-direction and Z-direction displacements of the oil pipeline by the two construction methods are shown in Figures 6 and 7, respectively.

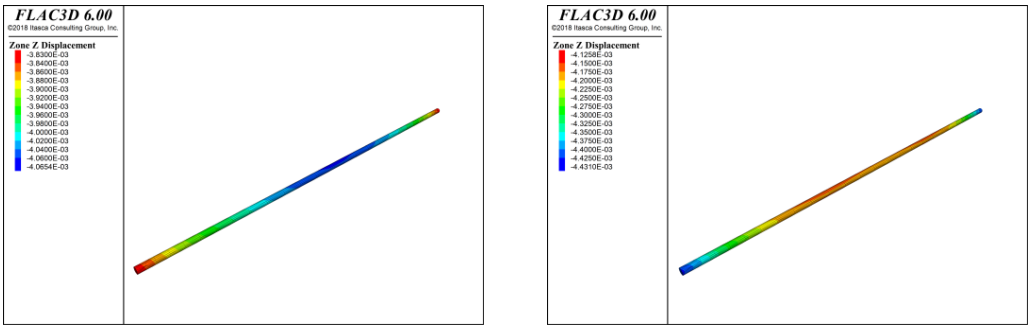
As can be seen from Figures 6 and 7, for the right bearing pile foundation construction of Wengcun No. 1 Bridge, the maximum horizontal displacements caused by conventional percussive drilling and rotary drilling for the pipeline were 2.04 mm and 0.22 mm, with a displacement increment of 1.82 mm, and the vertical displacements were 3.83 mm and 4.12 mm, with a displacement increment of 0.29 mm.

In particular, in order to verify the accuracy of the simulation, displacement monitoring points in X and Z directions were added at a point closest to the pile foundation, and then the same monitoring points were added 1 m before and after that point, with the layout shown in Figure 8.



(**a**) (**b**)

Figure 6. (**a**) X-direction displacement cloud of oil pipeline for rotary drilling method; (**b**) X-direction displacement cloud of oil pipeline for traditional percussion drilling method.



(**a**) (**b**)

Figure 7. (**a**) Z-direction displacement cloud of oil pipeline for rotary drilling method; (**b**) Z-direction displacement cloud of oil pipeline for traditional percussion drilling method.

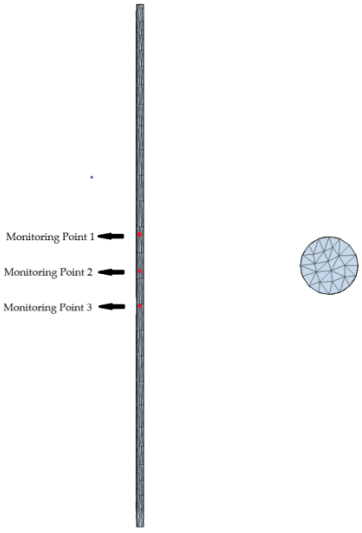
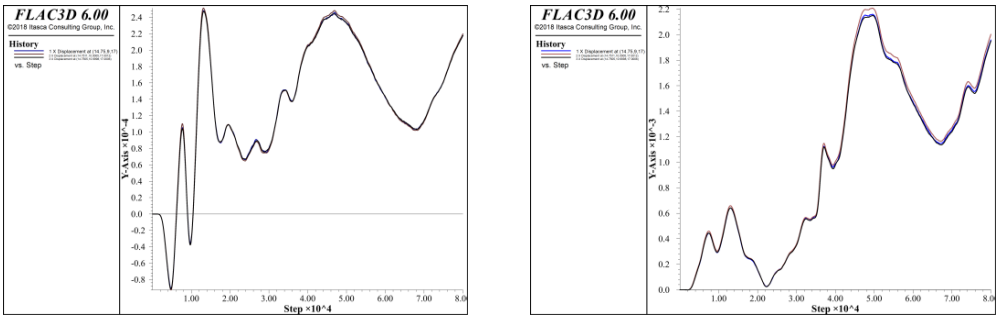


Figure 8. Schematic of the monitoring sites.

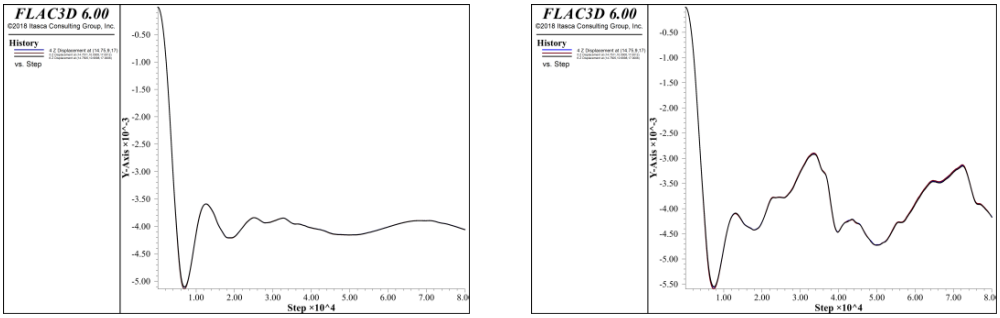
The effects of the two construction methods on the displacements in the X and Z directions of the monitoring points are shown in Figures 9 and 10, respectively.

As shown in Figures 9 and 10, the maximum horizontal displacements caused by traditional percussive drilling during pile foundation construction and rotary drilling during pile foundation construction at the monitoring point are 2.2 mm and 0.24 mm, with a displacement increment of 1.96 mm, and the displacements in the vertical direction are 5 mm and 5.5 mm, with a displacement increment of 0.5 mm, which is basically consistent with the results from the simulated cloud diagrams.



(**a**) (**b**)

Figure 9. (**a**) X-direction displacement monitoring map of monitoring points for rotary drilling method; (**b**) X-direction displacement monitoring map of monitoring points for traditional percussion drilling method.

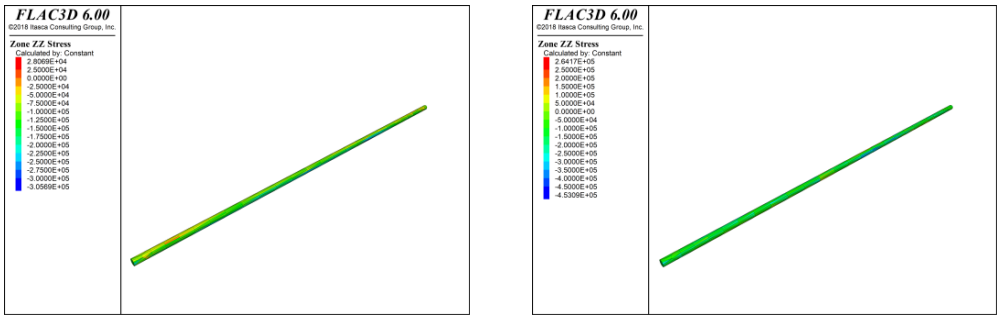


(**a**) (**b**)

Figure 10. (**a**) Z-direction displacement monitoring map of monitoring points for rotary drilling method; (**b**) Z-direction displacement monitoring map of monitoring points for traditional percussion drilling method.

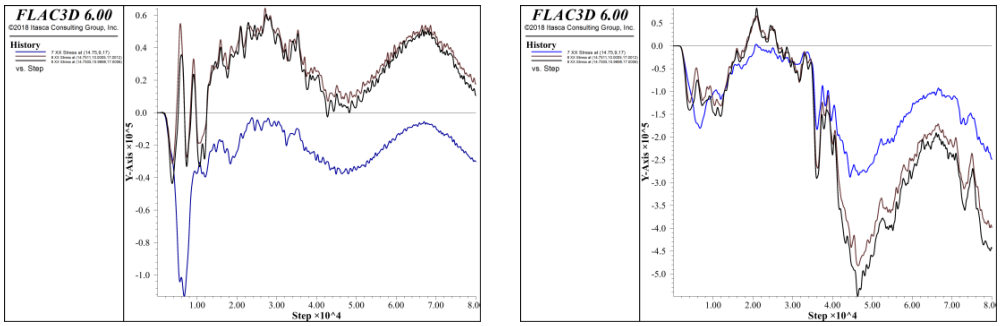
4.1.2. Construction Impact Stress Analysis

In order to analyze the stress response characteristics of the model after pile excavation, the X-direction stress and Z-direction stress generated in regard to the pipeline by the traditional percussive drilling pile excavation method and the rotary drilling method are simulated and analyzed, respectively. The X-direction and Z-direction stress maps of the pipeline for the two construction methods are shown in Figures 11 and 12, respectively.



(**a**) (**b**)

Figure 11. (**a**) Z-direction stress cloud of oil pipeline for rotary drilling method; (**b**) Z-direction stress cloud of oil pipeline for traditional percussion drilling method.

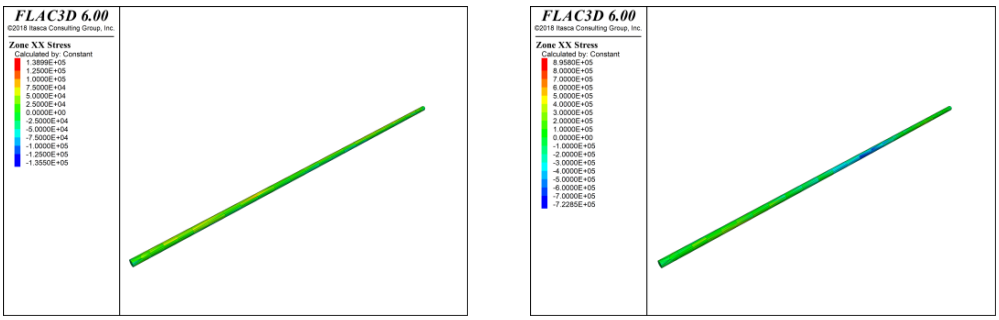


(**a**) (**b**)

Figure 12. (**a**) X-direction stress monitoring at monitoring points for rotary drilling method; (**b**) X-direction stress monitoring at monitoring points for traditional percussion drilling method.

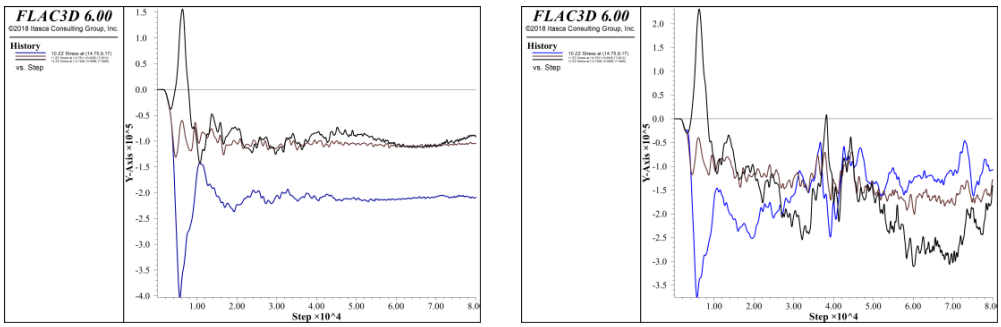
From Figures 11 and 12, it can be seen that the maximum stresses in the horizontal direction caused by the conventional percussive drilling pile foundation construction and rotary drilling pile foundation construction at the monitoring point are 8.9 MPa and 1.39 MPa, with a stress increment of 7.51 MPa, and in the vertical direction, 2.64 MPa and 0.28 MPa, with a displacement increment of 2.36 MPa. Similarly, the simulation is

performed again after the application of monitoring points. The stress monitoring diagrams in the X and Z directions at the monitoring points for the two construction methods are shown in Figure 13 and Figure 14, respectively.



(**a**) (**b**)

Figure 13. (**a**) X-direction stress cloud of oil pipeline for rotary drilling method; (**b**) X-direction stress cloud of oil pipeline for traditional percussion drilling method.



(**a**) (**b**)

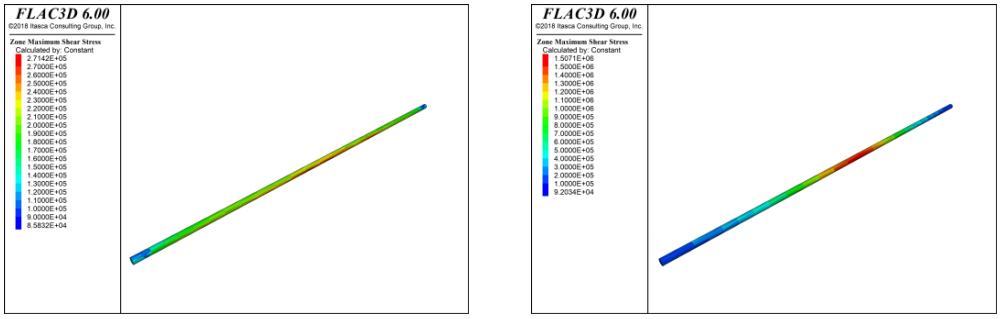
Figure 14. (**a**) Z-direction stress monitoring at monitoring points for rotary drilling method; (**b**) Z-direction stress monitoring at monitoring points for traditional percussion drilling method.

From Figures 13 and 14, the maximum stresses in the horizontal direction caused by the traditional percussive drilling pile foundation construction and rotary drilling pile foundation construction at the monitoring point are 5.5 MPa and 1.3 MPa, with a stress increment of 4.2 MPa, and the maximum stresses in the vertical direction are 3.74 MPa and 2.64 MPa, with a stress increment of 1.1 MPa. It is basically in line with the results from the simulated cloud diagrams.

Shear stress is the transverse cutting force generated within a material or structure, and it is very important for bridge pile construction adjacent to oil pipelines [27], as it directly affects soil stability, structural stability and the safety of the construction process. Therefore, shear stresses must be carefully considered and managed during bridge pile construction to ensure the reliability and safety of the pipeline system. It is worth noting that there is also a more significant difference between the shear stresses caused by the two construction methods on the pipeline, as shown in Figure 15.

From the analysis shown in Figure 15, it can be seen that the maximum shear stress caused by the traditional percussion drilling method of digging holes reaches 15 MPa, which has exceeded the permissible pressure (10 MPa) for the design of the pipeline of Guangxi Oil Transmission Department 2 of the South China Branch of the National Pipe Network Company. When oil transmission pipelines are subjected to a large amount of shear stresses, it may lead to the deformation of the pipeline material, which depends on the elasticity modulus and shear modulus of the material. In some areas of the pipeline, such as welded joints or bends, shear stresses may lead to stress concentrations [28], increasing the risk of fatigue or damage in these areas. If the shear stresses exceed the shear strength

of the pipe material, micro-cracks may develop in the pipe, which may expand over time and eventually lead to pipe rupture.



(**a**) (**b**)

Figure 15. (**a**) Maximum shear stress cloud of oil pipeline for rotary drilling method; (**b**) maximum shear stress cloud of oil pipeline for traditional percussion drilling method.

The maximum shear stress caused by the rotary drilling method is 2.71 MPa, which is much smaller compared to the traditional percussion drilling method and is lower than the allowable pressure of the pipeline design. The two construction methods affect the Lei comparative diagram, as shown in Figure 16.

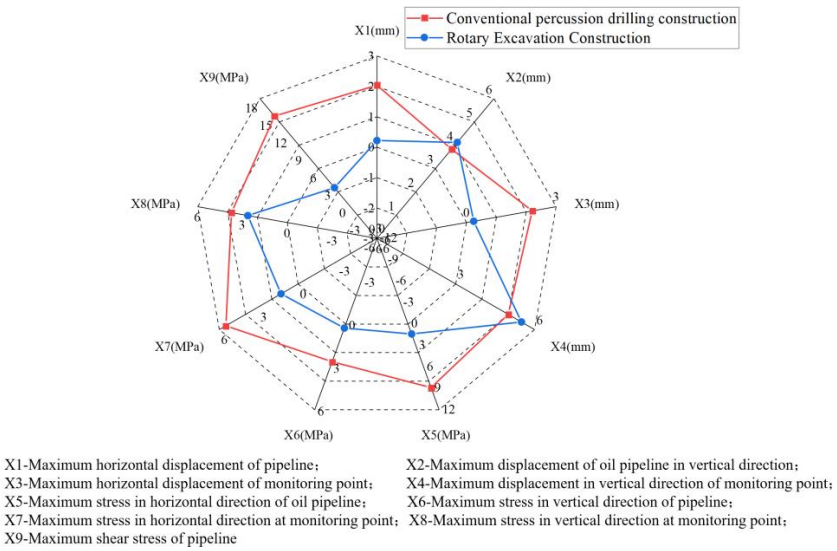


Figure 16. Impact diagram of the two construction methods compared to the design.

In summary, rotary piling construction has obvious mitigation effects in terms of both displacement and stress. From a displacement control point of view, the disturbance to the surrounding soil by rotary drilling is significantly smaller than that of percussive piling. In rotary drilling, the continuous rotation of the drill bit acts on the soil, resulting in less lateral displacement, which reduces the displacement and settlement of the neighboring soil layers. In contrast, conventional percussive piling, due to its intermittent impact force action [29,30], often results in larger lateral displacement and vertical settlement of the surrounding soil, increasing the risk of displacement of neighboring oil and gas pipelines or important buildings.

Secondly, in terms of stress distribution, the continuous force of the rotary piling method is more uniform, avoiding stress concentration due to the impact force. Percussive piling generates large dynamic stress waves in the soil around the pile during the construction process [31], which may lead to loosening and structural changes in the soil, thus affecting the overall bearing capacity and stability. In contrast, the rotary drilling

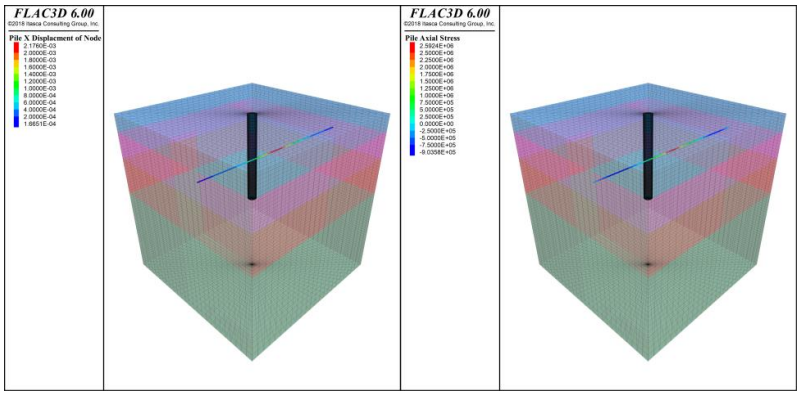
method maintains the continuity and consistency of the soil structure through a smooth rotary action, which reduces the soil damage caused by stress concentration.

4.2. Simulation of Different Construction Distances

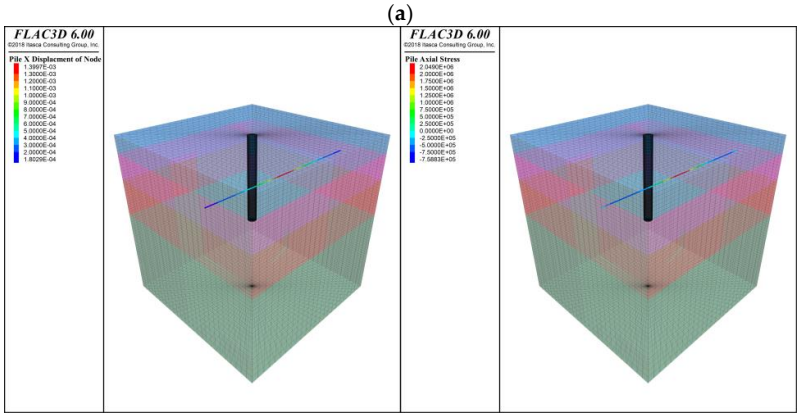
4.2.1. Simulation of Different Horizontal Construction Distances

Simulations were carried out for cases involving a horizontal distance of 3 m, 4 m, 5 m, 6 m, 7 m and 8 m, respectively, to explore the affected laws of oil and gas pipelines under different horizontal distances.

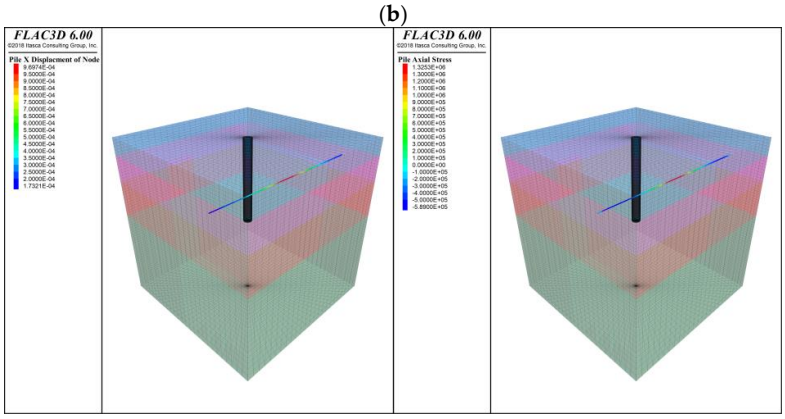
As shown in Figure 17, at varying horizontal construction distances, the displacement and X-direction stress cloud distribution exhibit similarities, with the peak displacement and axial stress manifesting at the center of the pipeline, nearest to the pile foundation. With a reduction in distance, the pipeline's displacement and peak stress progressively escalate. The maximum horizontal displacement escalates from 0.26 mm to 2.17 mm, and the peak axial stress rises from 0.53 MPa to 2.59 MPa. Additionally, the extent of the maximum stress progressively diminishes, leading to a pronounced stress concentration phenomenon.



(**a**)



(**b**)



(**c**)

Figure 17. *Cont.*

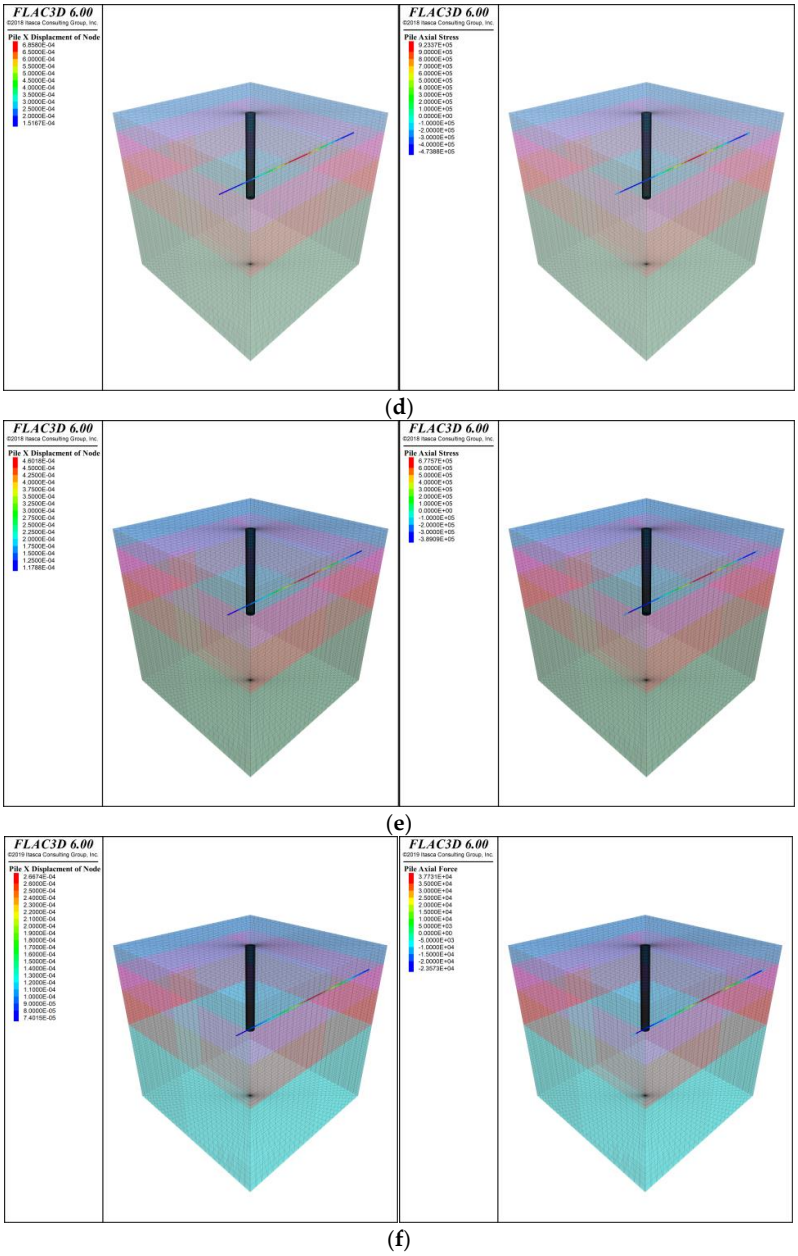


Figure 17. Pipeline X-direction displacement and stress cloud for different horizontal construction distances: (**a**) 3 m; (**b**) 4 m; (**c**) 5 m; (**d**) 6 m; (**e**) 7 m; (**f**) 8 m.

Monitoring points are established on the surface of the pipeline nearest to the pile foundation to track the horizontal displacements and stresses. The outcomes observed are then compiled and represented by a curve, as shown in Figure 18.

The graph clearly demonstrates that with a decrease in the horizontal construction distance, there is a noticeable increase in both the horizontal displacement and the axial stress experienced by the pipeline. In the displacement aspect, a linear increase is observed from the 8 m to 5 m interval, with a marked increase in the curve's slope from 5 m to 3 m, highlighting a distinct acceleration in the rate of displacement. The enhancement in the horizontal displacement per meter of reduction from 6 m to 3 m is quantified at 38.4%, 55.6% and 57.1%, respectively. The stress variation curve mirrors this trend, but with greater intensity; negligible changes occur within the 8 m to 5 m span, followed by a steep incline between 3 m to 5 m. At a horizontal construction distance of 3 m, the induced stress on the pipeline is approximately 2.5 times greater than that at 4 m, with the stress escalation per meter of reduction from 6 m to 3 m being 15.8%, 45.5% and 131.3%,

respectively. Consequently, both the horizontal displacement and axial stress on adjacent oil and gas pipelines during pile foundation construction exhibit a negative correlation with the construction distance, with a more pronounced increase in displacements and stresses at distances less than 5 m. Therefore, it is imperative to intensify the control over construction impacts when undertaking pile foundation construction within 5 m of oil and gas pipelines buried at a depth of 3 m, selecting suitable pile foundation construction techniques and impact mitigation measures in compliance with the designated design criteria.

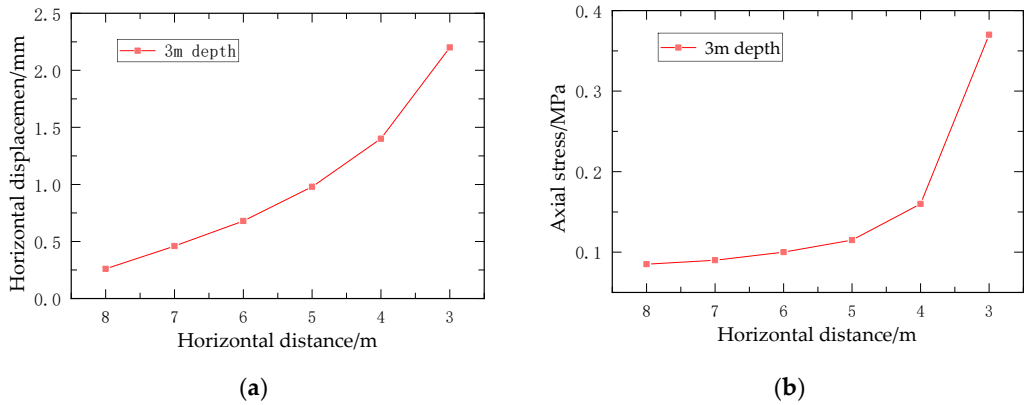


Figure 18. (**a**) Displacement variation curve for different horizontal distances; (**b**) stress variation curve for different horizontal distances.

4.2.2. Simulation of Different Burial Depths

In light of the actual conditions, the determination of the burial depth for oil and gas pipelines must consider a multitude of factors. While a deeper burial can safeguard the pipeline against external disturbances, the economic considerations and the complexities involved in regard to maintenance suggest that deeper is not always better. For this purpose, burial depths of 1 m, 2 m, 3 m and 4 m have been chosen for simulation and calculation to examine the behavior of horizontal displacement and stress responses at varying depths. The curves of horizontal displacement and stress variation under different working conditions are shown in Figure 19.

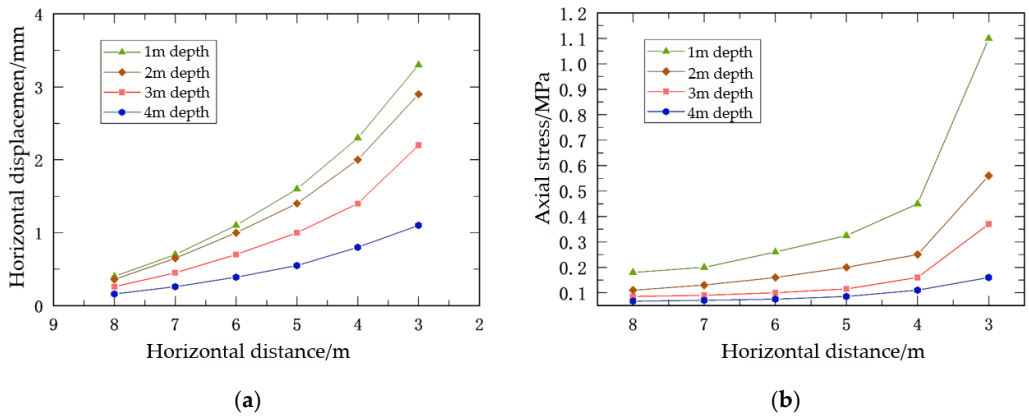


Figure 19. (**a**) Displacement variation curve for different horizontal distances; (**b**) stress variation curves for different horizontal distances.

Analyzing the first two figures, it can be observed that under different burial depth conditions, the displacement and stress experienced by the pipeline follow roughly the same pattern of change with regard to the construction distance, with both the displacement at the surface of the pipeline and the stress in the X direction increasing as the construction distance decreases. Under different burial depths, the maximum slope values of both the displacement and stress curves increase as the burial depth decreases. In terms of

displacement, overall, as the burial depth becomes shallower, the maximum displacement continues to grow, but the rate of growth becomes progressively smaller. Conversely, in regard to stress, the rate of increase in regard to the maximum stress grows larger as the burial depth decreases. This phenomenon is primarily due to the following reasons: the stiffness of the soil increases with depth because the pressure makes the lower layers of soil more compact. As the burial depth decreases, the soil may offer less resistance to pipeline displacement, leading to a smaller increase in the displacement impact. In terms of stress, under conditions of shallow burial, the soil surrounding the pipeline may not sufficiently transfer and distribute stress. This may lead to stress concentration in the soil around the pipeline, resulting in higher stress on the pipeline. As the burial depth increases, the soil layers can better disperse these stresses, reducing their direct impact on the pipeline. Therefore, stress experiences a faster increase at shallower burial depths.

In summary, the pattern of displacement change does not show significant variation with decreasing burial depth, while a more pronounced increase in the slope of the stress curve can be clearly seen after the burial depth decreases to 2 m. Therefore, in actual engineering projects encountering pipelines with a burial depth not exceeding 2 m, greater attention should be paid to the stress impacts caused by construction.

5. Conclusions

Combining practical engineering situations, this study uses numerical simulation to compare the differences in the vibration and stress effects caused by two different pile foundation construction methods. Additionally, it explores, debates and puts forward conclusions on the variances in the construction effects attributed to different scenarios within the rotary drilling process. The findings are as follows:

- Compared with traditional impact pile driving construction, the rotary drilling method for pile foundation construction reduced the horizontal displacement of the pipeline by 90%, the vertical displacement by 10%, the horizontal stress on the pipeline by 85% and the vertical stress by 30%;
- During pile foundation construction, both the horizontal displacement and axial stress of the adjacent oil and gas pipelines are negatively correlated with the construction distance. When the construction distance is less than 5 m, if the horizontal distance continues to decrease, the increase in displacement and stress will be much faster than previously. Therefore, it is recommended that the minimum distance between pile foundation construction and oil and gas pipelines should not be less than 5 m;
- An analysis from the perspective of burial depth shows that the pattern of displacement changes does not exhibit significant alterations as the depth decreases. However, a marked increase in the slope of the stress curve can be distinctly observed once the burial depth is reduced to 2 m. Therefore, in practical engineering projects, when encountering pipelines with a burial depth of less than 2 m, greater attention must be paid to the stress impacts caused by construction. It is noteworthy that with a reduction in the burial depth or a decrease in the horizontal construction distance, the phenomenon of stress concentration on the pipelines becomes more pronounced;
- In the case of pile foundation construction near oil pipelines or important buildings, rotary drilling is preferred if environmental conditions permit. This method can effectively minimize the impact on the surrounding environment and structure and ensure construction safety and efficiency.

The results of the numerical simulations indicate that when considering both vibration and stress control, rotary drilling pile foundation construction has a clear advantage over traditional impact pile construction in terms of vibration and stress management. This study also summarizes the patterns on how different working conditions affect pile foundation construction. However, this paper has its limitations, lacking related field experiments. If microseismic experiments and vibration monitoring could be conducted, it would be possible to further verify the accuracy of the conclusions. Additionally, the

impact of varying geological and weather conditions on vibrations during pile foundation construction is significant, which this study did not take into account.

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