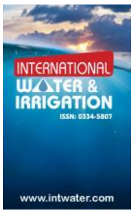

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# Field Test and Numerical Simulation of Jacking Force of Reinforced Concrete Pipe Jacking in Long Distance Composite Formation

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**Abstract**: Jacking force is one of the important parameters of pipe jacking construction. In order to analyze the mechanical properties of large-diameter reinforced concrete pipe jacking construction in composite strata, based on the reinforced concrete pipe jacking project of the Jiaoliu River pressureless cave of Inner Mongolia water diversion project from ChaorHe to Liaoning, the jacking force, face resistance, circumferential pressure and strain were monitored. According to the field measured data, the friction coefficient of the pipe jacking through different strata was calculated. Then, the three-dimensional finite element model of pipe jacking construction is established by ABAQUS numerical simulation software. The calculated friction coefficient is substituted into the numerical model. The simulated jacking force is calculated by the numerical simulation results. The measured jacking force, the simulated jacking force and the predicted jacking force based on the prediction model of jacking force proposed by Staheli are compared. The results show that compared with the predicted jacking force, the simulated jacking force is consistent with the measured jacking force, which indicates that the parameters obtained based on the field measured data are substituted into the numerical model. The accuracy of the calculated numerical simulation results is very high. The method of predicting the jacking force in this study can also provide a reference for similar projects in the future.

**Keywords**- reinforced concrete pipe jacking; jacking force; composite strata; friction coefficient; numerical simulation

## 1. Introduction

Pipe jacking method is an efficient, safe and environmentally friendly trenchless pipeline/tunnel construction technology, which is known as an environmentally friendly technology for underground facilities together with other trenchless technologies[1]. With the acceleration of urbanization, the traditional excavation construction method is gradually restricted, and pipe jacking technology has been more and more used in the construction of municipal pipeline networks, comprehensive pipeline corridors, underground passages and other urban underground projects due to its ad-vantages of little interference with the ground and short construction period[2][3]. The core of pipe jacking construction lies in how to effectively control and calculate the jacking force, which is not only one of the decisive parameters for the design of pipeline structure, microtunnel boring machine selection and the design of working shaft structure, but also relates to the stability of the surrounding soil and construction safety, and affects the progress and quality of construction. When the jacking force is small, the overall jacking speed of the pipe is slow, delaying the construction period. When the jacking force is too large, the compressive stress on the pipe increases, and local damage occurs when it exceeds the ultimate bearing capacity of the pipe, which increases the risk of instability of the pipeline structure. Therefore, the effective prediction of the jacking force plays an indispensable role in guaranteeing the safety of pipe jacking construction.

In terms of jacking force research, Staheli[4] studied the friction coefficient between six kinds of pipes and two kinds of soil under different roughness by direct shear test, analyzed the influence of roughness on the shear mechanism of pipe-soil interface, modified Terzaghi arch theory, and put forward the calculation formula of earth pressure and jacking force between pipe and soil. Peng Zhang et al.[5] analyzed the pipe-soil contact angle and contact pressure distribution law based on the Persson contact model, and based on this basis, derived a linear pipe jacking friction formula by considering pipe slurry friction. Tianshuo Xu et al.[6] deduced a formula for calculating the face resistance of pipe jacking in rock formation by analyzing the rock-breaking mechanism, force model and influence law of the cutter head hob of the rock pipe jacking machine; Shou et al.[7] studied the influence of factors such as mud and over-excavation on the jacking force of pipe jacking through indoor tests and finite element simulations. Zhenxing Xue et al.[8] used ANSYS software to analyze the influence laws of jacking proximity, burial depth, pipe diameter, pipe and rectification angle on the stress of concrete pipes. Yen et al.[9] used ABAQUS software to establish the jacking force of pipe jacking models under different contact areas and different slurry additives lubrication conditions, and obtained the effects of contact area and slurry additives on the jacking force of pipe jacking. Ji et al.[10] proposed a method to predict the jacking force of the pipe jacking through the particle model. By calibrating the microscopic parameters of the sand, the particle model can reproduce the macroscopic material behavior of the sand, so as to derive the contact pressure around the pipe. Then the interface friction coefficient is used to evaluate the friction resistance of the pipe jacking. Yang et al.[11] conducted research on the jacking force of densely arranged pipe jacks in the pipe-roof pre-construction method. Zhong et al.[12] assessed experimental friction parameters and contact properties of pipe strings to address pipe stuck issues in rock pipe jacking projects. Wen et al.[13] conducted a numerical and theoretical study on jacking force prediction in slurry pipe jacking traversing frozen ground, while Sheil[14] proposed a probabilistic observational approach for predicting microtunneling jacking forces. Zhou et al.[15] focused on predicting jacking force using PSO-BPNN and PSO-SVR algorithms in curved pipe roofs, highlighting the importance of advanced prediction methods in tunneling projects.

In summary, the current research methods for the jacking force of pipe jacking include indoor tests, field monitoring, theoretical calculations and numerical simulation, etc. Since numerical simulation means can quickly determine the engineering behavior of soil-pipe interaction[16][18] , the numerical simulation has been favored by many scholars. However, most of the existing numerical simulations of jacking focus on the pipe-soil contact area, the size of the friction coefficient, and the jacking control method, and ignore the influence of the nature of the composite stratum on the simulation parameters, and most of the friction coefficients in the simulation are selected by the assumption method, which is not based on the actual basis. Therefore, this paper calculates the friction coefficients of different jacking stages by combining the measured data of reinforced concrete pipe jacking project, and establishes a three-dimensional model of pipe jacking by using ABAQUS finite element software to analyze in detail the influence of the change of stratum properties on the jacking force in the process of jacking, and verifies and compares the data with the actual monitoring data, to explore a more accurate prediction method of the jacking force, and to further guarantee the safety of the structure in the process of pipe jacking.

## 2. Project Profile

This study relies on the reinforced concrete pipe jacking project of the Jiaoliu River pressureless cave of Inner Mongolia water diversion project from ChaorHe to Liaoning, is located in the Inner Mongolia Autonomous Region Xing'an League, Tuquan County, for the northeast to southwest oriented straight-line pipe jacking tunnel, the total length of the project section is 1115 m. The project section consists of expanding the chamber section, pipe jacking section and pressureless cave drilling and blasting section, the jacking of the pressureless cave section of the length of 940 m, the maximum burial depth of 26 m, specific drop 1/1100, the use of straight-line jacking construction method, a one-time jacking through. It adopts straight line pipe jacking construction method to jack through at one time.

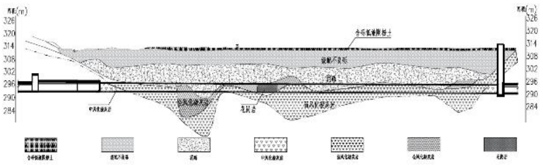


**Figure 1.** Geological conditions of the pipe jacking crossing section of the Jiaoliu River.

The geological conditions of the pipe jacking crossing section are complex, and the overall performance is "upper soft and lower hard". As shown in Figure 1, the main crossing strata are tuff, mud gravel and granite. The saturated compressive strength of the tuff is 67MPa~98.7MPa, and the saturated compressive strength of the granite is 35MPa~51MPa. The pipe jacking is generally pushed into the fully strongly weathered layer of mud gravel and bedrock, and locally there are weak weathered layers. The rock layers are different in hardness. There is a compound of mud gravel and highly weathered tuff strata. The upper soft and lower hard layers are formed. Problems such as deflection of the microtunnel boring machine and the pipe sticking can easily occur during jacking at the formation interface.

The pipe jacking construction uses C50 prefabricated reinforced concrete pipes with an inner diameter of 3600mm, an outer diameter of 4300mm, a single section length of 2500mm, and an impermeability level of P10. The interface adopts a flexible "F" type interface and a wedge shaped double rubber ring. The structure of the pipe section is shown in Figure 2. The inner and outer layers of longitudinal and ring bars are composed of 12mm HRB400 steel bars. The spacing between ring bars is 40mm, and the angular spacing between the longitudinal bars is 6°. The inner surface concrete protective layer of the pipe section is 40mm thick, and the outer surface protective layer is 50mm thick. Six grouting holes are evenly arranged every 60° along the pipe circumference at the socket end of the pipe section. During actual construction, only five grouting holes were used, and one grouting hole at the bottom of the pipe jacking was not used.

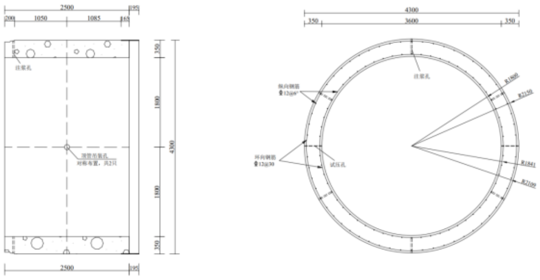


**Figure 2.** Schematic diagram of pipe structure.

## 3. Measurement and Analysis of Pipe Jacking Construction

### 3.1 On-Site Monitoring

During the jacking process of large-diameter pipe jacking in composite strata, different strata are frequently crossed. In order to ensure the safety of the pipe structure during the actual pipe jacking construction, steel bar strain gauges, soil pressure gauges, and pore water pressure gauges are used to monitor the stress parameters of the pipe in the field test. The monitoring content of stress parameters includes contact pressure around the pipe, water pressure outside the pipe, axial steel bar strain and circumferential steel bar strain. The monitoring section of this pipe jacking project is arranged on the 38# pipe, and the monitoring section layout is shown in Figure 3. A total of 4 monitoring points are arranged on the monitoring section. Each monitoring point is equipped with an earth pressure sensor (numbered E-1-E-4), a pore water pressure gauge (numbered P-1-P-4), an axial reinforcement strain gauge (numbered A-1-A-4) and a circumferential reinforcement strain gauge (numbered H-

1-H-4). The axial reinforcement strain gauge and longitudinal reinforcement strain gauge are welded to the outer reinforcement cage. The on-site layout is shown in Figure 4.

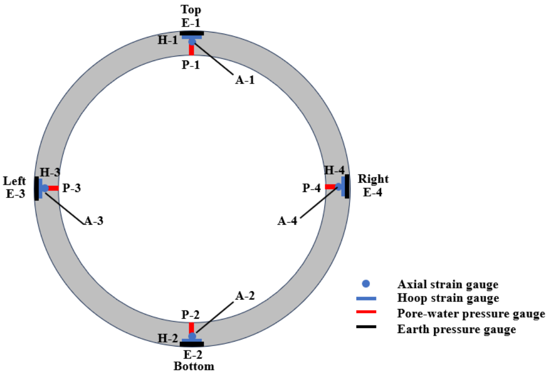
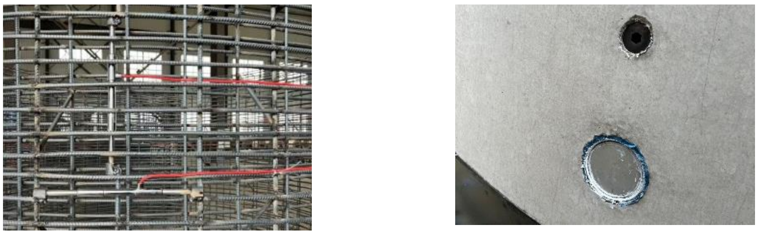


**Figure 3.** Layout of monitoring sections.



(a) Reinforcement gauge installation

(b) Installation of pore water pressure gauges and soil pressure gauges

**Figure 4.** Sensor site layout.

### 3.2 Measured Analysis of Jacking Force

As the total jacking distance was 940m long, with the increase of jacking distance, the intermediate jacking station was used many times, which led to the inaccuracy of the measured total jacking force. Therefore, the jacking section of the first 250m was selected for the study. In this jacking interval, the intermediate jacking station was not activated, and the construction used the main jacking cylinder for jacking, and the total jacking force was the total jacking force of the total jacking cylinder thrust.

The on-site jacking force is calculated by installing a pressure transmitter at the oil outlet main pipe of the main jack pumping station to obtain the oil pressure and multiplying it by the relevant parameters such as the jack area. The change curve of the on-site measured jacking force versus jacking distance is shown in Fig.5. Within 30 m of the jacking process, the pipe mainly passes through the moderately weathered tuff. In the early stage of jacking, the lubricating mud has not yet exerted its effect and the strong weathered tuff cracks are more likely to cause mud loss. The friction coefficient of the pipe-soil contact interface is large, and the jacking force increases rapidly. However, with the increase of jacking distance, the lubricating mud gradually plays a role, and a complete mud sleeve is formed around the pipe. The friction between the pipe and the soil changes to the friction between the pipe and the mud, and the friction coefficient is greatly reduced, which makes the jacking force growth trend gradually slow down, and there is a slight decrease in the local area; within the range of 30-90 meters, the pipe enters the highly weathered tuff formation from the moderately weathered tuff formation, and the jacking force fluctuates around 15000kN. At 90 meters, the pipe jacking entered the composite formation of highly weathered tuff and fully weathered tuff. Due to the loose nature and instability of fully weathered tuff, it would lead to greater face resistance and side friction, so the jacking force quickly increased to about 21000kN. At 110m, the pipe jacking enters the "soft at the top and hard at the bottom" composite formation composed of mud gravel and highly weathered tuff. The existence of mud gravel will certainly increase the face resistance slightly, but the drainage and fluidity between its particles will greatly reduce the frictional resistance around the pipe, so the jacking force drops sharply when first entering the composite formation; When the jacking reached 170 meters, the pipe jacking machine entered the highly weathered tuff formation again. The jacking force increased sharply and then gradually stabilized. The average jacking force increased by 37.03% compared with the composite formation of mud gravel and highly weathered tuff, and it continued to increase with the increase of the distance between the top. Due to the thixotropy of bentonite mud, and the construction interruption caused by hoisting and connecting pipes causes repeated loading and unloading processes in the axial direction of the pipes. The static friction force after construction is stopped and restarted is greater than the sliding friction force during normal jacking , so the measured jacking force increases in a fluctuating manner throughout the jacking process.

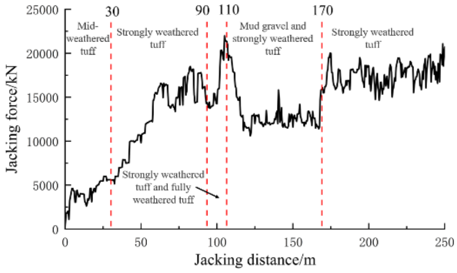


**Figure 5.** Variation of measured jacking force with jacking distance curve

### *3.3.* Measured Analysis of Face Resistance

As an important part of the jacking force, face resistance is not only related to the stability of the excavation face, but also an important construction parameter to evaluate the wear of the toolhead of the microtunnel boring machine. The on-site measured face resistance changes with the top proximity distance are shown in Figure 6. In the early stage of jacking, due to equipment failure, data on face resistance within the first 30 meters was not collected. In the range of 30-90 meters, pipe jacking passes through highly weathered tuff formations, with an average face resistance of approximately 1.8 bar. It can be seen from Figure 6 that the face resistance fluctuates greatly within this range. It is speculated that the weathering degree and strength of highly weathered tuffs may differ greatly, and the stability of the strata is uneven. This unevenness will cause the pipe jacking machine to encounter different soil layers and rock formations during the jacking process, causing fluctuations in face resistance. At 90m, the pipe jacking entered the fully weathered tuff and the highly weathered tuff composite formation from the highly weathered tuff formation. Due to the loose nature of the fully weathered tuff, the face resistance increased slightly and fluctuated around 1.9 bar. At 110m, the pipe jacking enters the upper soft and lower hard formation composed of mudgravel and highly weathered tuff. Since mudgravel is lower in strength and loose in structure than tuff, the tunnel face requires greater pressure to ensure the balance of the formation. In addition, the soil cut by the cutter head in the mud-gravel formation tends to gather in front of the cutter head, which causes the torque of the cutter head to increase abnormally. It is necessary to increase the mud pressure additionally to avoid this phenomenon. Therefore, the face resistance in this formation increases from 1.9 bar to 2.16 bar. In the range of 170-250m, the microtunnel boring machine once again entered the highly weathered tuff formation, and the face resistance gradually decreased from 2.16 bar and the fluctuations were still large, which was consistent with when the microtunnel boring machine was pushed in the range of 30-90m. The average face resistance in the range of 170-250m was calculated to be approximately 1.88 bar. Through the analysis of the measured face resistance, it can be seen that the change of face resistance is related to the weakness of the pipe jacking head through the formation, and the face resistance is greater when pushing in weak and loose formations.

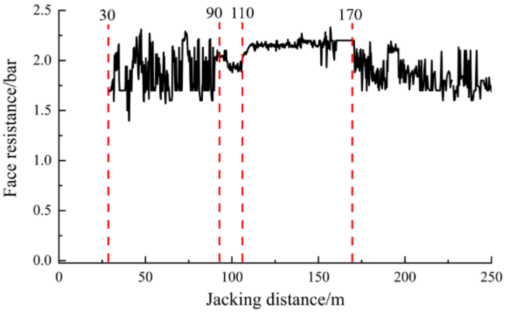


**Figure 6.** Measured headway resistance variation curve with jacking distance

### 3.4. Measured Inverse Friction Coefficient

For reinforced concrete pipe jacking, the axial strain is mainly controlled by the jacking force . Figure 7 shows a schematic diagram of the stress on the section of a pipe. Select any pipe, and the difference between the axial internal force of the pipe and the face resistance of the microtunnel boring machine should be equal to the resultant force of the circumferential friction resistance of all pipe between the pipe and the microtunnel boring machine. Therefore, between the NO.i pipe and the microtunnel boring machine, the friction coefficient between the pipe wall and the soil and the axial internal force of the pipe section should have the following relationship:

$$F_i - N = E\overline{\varepsilon_i}A - N = \mu F_c L \qquad (1)$$

where: $i$ represents the No.i pipe. $F_i$ is the resultant force of the axial internal force of the No.i pipe; $N$ is the face resistance of the microtunnel boring machine; $\overline{\varepsilon_i}$ is the average axial strain of the No.i pipe; $E$ is the average elastic modulus of reinforced concrete pipe, and is 35879.03MPa based on the actual reinforcement ratio; $A$ is the cross-sectional area of the pipe, which is 4.34m$^2$ based on the size of the pipe; $\mu$ is the friction coefficient between the outer wall of the pipe and the surrounding soil; $F_c$ is the contact pressure between pipe wall and soil; $L$ is the jacking distance;

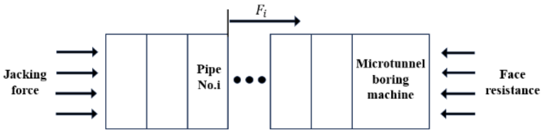


**Figure 7.** Schematic diagram of pipe forces

When the microtunnel boring machine jacked to 250m, the 38# pipe was 155m away from the cave door, and there was no monitoring data in the first 30m at the initial stage of jacking due to equipment failure, so only the data of the 38# pipe traversing the stratum of 30-155m were obtained. In view of the short distance between fully weathered tuff and strongly weathered tuff mixed strata, and the monitoring data is not much different from the strongly weathered tuff strata in the whole section, in order to facilitate the calculation, the strata within the range of 30-110m are regarded as the strongly weathered tuff strata in the whole section, and the average on-face resistance is taken to be 1.83bar.$F_c$ According to the monitoring data of soil pressure around the pipe, the average values of 30-110m and 110-155m are 221.78kPa and 196.15kPa respectively, and the average axial compressive strain of 38# pipe when jacking up to 30m and 110m are 87.1με and 56.67με, respectively, and the corresponding parameter is substituted into Equal (1) to calculate the friction coefficients of the pipe-soil in the different strata. The calculation results are as shown in Table 1. It is found that the pipe-soil friction coefficient in the composite layer of mud gravel and strongly weathered tuff is reduced by 14.8% compared with that in the strongly weathered tuff in the whole section, which is due to the composition and shape of the mud gravel particles are different and more heterogeneous, and this inhomogeneity leads to the increase of relative mobility between particles of the soil body under the action of stress, which then reduces the friction between the contact surfaces of the pipe-soil.

**Table 1.** Friction coefficients by stage

| Jacking position (m) | stratum (geology) | Average coefficient of friction |
|---|---|---|
| 30-110 | Strongly weathered tuff formation | 0.61 |
| 110-155m | Complex formation of mud gravels and strongly weathered tuffs | 0.52 |

## 4. Simulation of Jacking Process

### 4.1. Model Establishment

According to the results of the inverse calculation of the pipe-soil friction coefficient, a three-dimensional jacking numerical model was established using ABAQUS. For the characteristics of this project, the following assumptions are used to simplify the simulation process:

(1) The traversing soil is assumed to be a homogeneous, continuous, isotropic elastic-plastic body, and the Druker-Prager principal model is used.

(2) The pipe and microtunnel boring machine are simulated by solid units, ignoring the role of pipe joints, and the whole pipe is regarded as a whole structure, and the elastic intrinsic model is adopted.

(3) For the simulation of reinforced concrete pipe, instead of considering the effect of reinforcement bars in the pipe joints on the overall performance of the pipe joints individually, it is assumed that the reinforcement bars are uniformly distributed in the pipe and the mechanical properties of the reinforcement bars are directly imposed on the pipes by calculation;

(4) Assuming that the slurry pressure acts uniformly on the soil, a uniform pressure is applied to the soil outside the pipe wall in the jacking analysis step in a direction perpendicular to the pipe wall outward to enable the simulation of the injection pressure.

(5) The effect of groundwater seepage on soil disturbance during jacking is not considered.

In order to better simulate the jacking process, the model parameters are set as follows:

(1) Model framework construction and grid division

In this paper, ABAQUS software is used to establish a three-dimensional finite element model of pipe jacking construction, taking into account the boundary effect, the model stratum width is set to 38m, height is 45m, length is 280m, the stratum mesh model is shown in Fig. 8, the outer diameter of the condensed soil pipe component is 4.3m, inner diameter is 3.6m, wall thickness is 0.35m. The soil, microtunnel boring machine and pipe are all classified according to the C3D8R entity unit, and the calculation model and grid division are shown in Figure 9.

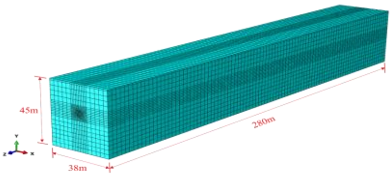


**Figure 8.** 3D model of the soil.

**Figure 9.** 3D model of pipe and microtunnel boring machine.

(2) Material parameters

The first 250m of microtunnel boring machine is mainly jacked in mud gravel and strongly weathered tuff strata, and the strata are divided into 4 layers from top to bottom, which are gravel-bearing low liquid limit clay, graded poor gravel, mud gravel, and strongly weathered tuff in order, as shown in Fig. 10, and the mechanical parameters of each stratum material are shown in Table 2.

**Table 2.** Mechanical parameters of each material.

| Soil layer structure | Thickness (m) | Cohesion(kPa) | Angle of internal friction (°) | Modulus of elasticity (MPa) | Heaviness ($kN/m^3$ ) | Poisson's ratio |
|---|---|---|---|---|---|---|
| gravelly low-liquid-limit clay | 1 | 8.5 | 25 | 15 | 19.0 | 0.3 |
| poorly graded gravel | 6.5 | 0 | 29.5 | 100 | 21.0 | 0.22 |
| gravel | 6.5 | 6.5 | 28 | 125 | 21.0 | 0.31 |
| strongly weathered tuff | 31 | 100 | 28 | 30000 | 25.5 | 0.35 |
| microtunnel boring machine | — | — | — | 200000 | 78.5 | — |
| Concrete pipe joints | — | — | — | 35879.03 | 26.0 | 0.2 |

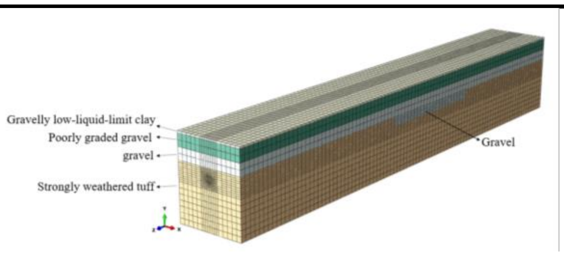


**Figure 10.** Stratigraphic Material Properties Map.

(3) Pipe-soil contact: The contact pair is set between the soil and the outer surface of the corresponding pipe, and the friction between the two is expressed by the tangential behavior through the definition of the friction coefficient of the "penalty function", which is set according to Table 3. In order to simulate the effect of lubricating mud on the pipe-soil contact, and at the same time consider the stratigraphic loss of the surrounding soil, there is an isodic layer unit set up between the excavated tunnel and the pipe to simulate the mud set, and the contact

interface between the isodic layer and the tunnel adopts the common node constraint method, and the thickness adopts the actual overcutting amount of 30 mm. It should be noted that, in the simulation of the microtunnel boring machine traversing through the upper-soft and lower-hard strata, it is set up that the upper half of pipe contact with the gravels and the lower half with the strongly weathered condensed concrete. The lower half surface is in contact with strongly weathered tuff, while the pipe-soil friction coefficient in the composite formation of mud gravel and strongly weathered tuff in the previous section is the average friction coefficient. Therefore, the average friction coefficient value obtained previous section is regarded as the weighted average of the friction coefficients of the tube-soil contact interface between the two formations. According to the geological exploration report, the tube-soil friction coefficient of the formation in pure mud gravel is inversely calculated to be 0.43.

**Table 3.** Recommended values for friction factor for concrete pipe jacking.

| contact surface material | coefficient of friction | Fluid friction (lubrication) |
|---|---|---|
| Concrete with strongly weathered tuff | 0.61 | 0.1-0.3 |
| Concrete and gravel | 0.43 | |

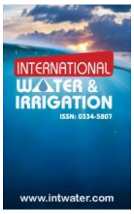
(4) Boundary conditions and load application: the lower surface of the model restricts the displacements in three directions, and the sides restrict their respective normal displacements. The pipe jacking adopts displacement control method[19][20]. The displacement load is applied to the end face of the last pipe, and the end face of the pipe in this paper is simulated by applying a displacement of 2.5m along the axial direction, in order to simulate the length of the microtunnel boring machine jacking the root pipe forward in the actual construction.

(5) Analysis steps: firstly, the soil body is balanced by ground stress, then the pipe is jacked into the preset pipe hole as the initial jacking state, and the excavation jacking process is simulated by the birth-death unit method and the displacement control method, and the simulated jacking mileage and geological conditions are as follows: 37.5-40m, 87.5-90m (strongly weathered tuff stratum), 117.5-120, 162.5-165m (composite stratum of mud and strongly weathered tuff), 187.5-190m, 247.5-250m (strongly weathered tuff stratum), 187.5-190m, 247.5-250m (strongly weathered tuff stratum). weathered tuff composite stratum), 187.5-190m, 247.5-250m (strongly weathered tuff stratum).

4.2. Analysis of Numerical Simulation Results

The displacement control method is used in the simulation of this study. The displacement load is applied at the end of the pipe to control the pipe to advance along the Z-axis direction and it is assumed that the influence of the earth pressure around the pipe in the X and Y axis directions on the axial stress of the pipe is limited. Therefore, the stress component of the pipe in the Z-axis direction in the simulation results can be regarded as the stress mainly affected by the jacking force during the jacking force process. Therefore, the jacking force applied to the pipe can be deduced and calculated by using the stress of the end face of the pipe. In order to simplify the calculation, the axial stress value is extracted from each node of the end face of the pipe, and the average value is calculated, and then multiplied by the cross-sectional area of the pipe to obtain the specific value of the jacking force. The area of the jacking end face is 4.34 m2. Then, the relevant data obtained in the previous article are substituted into the jacking force prediction model proposed by Staheli[4] , and the jacking force of the pipe at the jacking mileage of 37.5-40m, 87.5-90m, 117.5-120,162.5-165m, 187.5-190m, 247.5-250m is calculated. The predicted jacking force value calculated by the numerical simulation calculation and the jacking force prediction model proposed by Staheli is compared with the measured jacking force, as shown in Figure 11. It should be noted that the measured jacking in Fig.11

From Figure 11, it can be seen that in the jacking section of 38.5-40 m, the simulated jacking force is in good agreement with the actual jacking force, with a difference of 4.9 %, while the predicted jacking force is 22.5 % and 28.5 % larger than the former two respectively. In the jacking process of the 87.5-90 m jacking section, the predicted jacking force is as high as 20109.38 kN, which is far greater than the measured jacking force and the simulated jacking force, while the measured jacking force and the predicted jacking force are about 6.1 %. In the



jacking sections of 117.5m-120m and 162.5-165m, the pipe passes through the composite strata of mud gravel and strongly weathered tuff, and the simulated jacking force is about 15.9 % and 17.7 % higher than the measured jacking force, respectively. The reason for this phenomenon may be that in the actual jacking process, part of the mud gravel will enter the annular space after the cutterhead cuts the soil, and the water or fine particles contained in the mud gravel soil can play a lubricating role and reduce the friction between the pipeline and the soil. And when the mud gravel soil is subjected to external forces, it can undergo a large degree of deformation, so that the soil in the jacking process can adapt to the movement of the pipeline more smoothly and reduce the jacking force. However, in the process of numerical simulation, there is no phenomenon that the soil enters the annular space gap, so the simulated jacking force is slightly larger than the measured jacking force as a whole. In general, the three jacking forces have little difference in the initial stage of jacking, but the predicted jacking force is greater than the measured jacking force and the simulated jacking force. The predicted jacking force in the middle and late stages is far greater than the measured jacking force and the simulated jacking force. The trend of the latter two is consistent from beginning to end, which proves that the numerical model established in this study has certain accuracy.

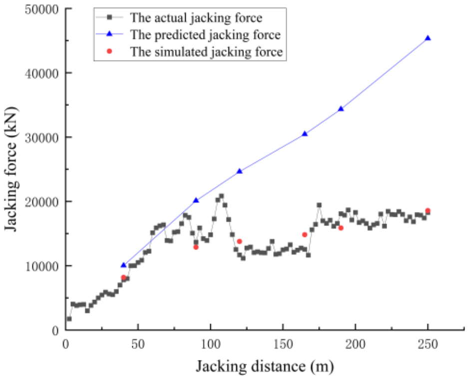


**Figure 11.** Comparison between simulated jacking force and measured jacking force.

## 5. Conclusion

Through field tests on pipe jacking in long-distance composite strata and numerical simulation of jacking force, the following conclusions are obtained:

(1) During the process of reinforced concrete pipe jacking through composite strata, the time effect of grouting action and the influence of changes in stratum properties on the jacking force show regularity in time and space. In terms of time, due to the time effect of grouting, the jacking force in the early stage of grouting increases rapidly. When a complete slurry sleeve is formed around the pipe, the growth of the jacking force gradually slows down and becomes stable; in space, the jacking force is affected by the formation. Seriously, the concrete manifestation is that after the jacking force enters the upper soft and lower hard composite formation from the full-section rock formation, the jacking force suddenly increases, and then enters the full-section rock formation again, the jacking force increases sharply and continues to increase overall. trend.

(2) The friction coefficient calculated based on head-on resistance and axial strain is greatly affected by the properties of the formation. The friction coefficient is 14.8% lower in the composite formation of mudgravel and highly weathered tuff than in the full-section highly weathered tuff.

(3) The early trends of simulated jacking force, predicted model jacking force and measured jacking force are consistent, but the predicted jacking force is slightly larger than the measured jacking force and simulated jacking force. In the middle and late stages, the predicted jacking force is much larger than the measured jacking force and the simulated jacking force, while the simulated jacking force is consistent with the measured jacking force.

It shows that the accuracy of the numerical simulation results calculated by substituting the friction coefficient of the construction site into the numerical model is high, which provides reference for similar projects in the future.

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