Selection of jacking sequence and jacking parameter analysis of multi-row jacking pipes in water-rich sand

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Abstract. For the purpose of safe and efficient construction of multi-row pipe jacking in water-rich sand layer, a case study was carried out, taking the three-row pipe jacking project of the water-rich sand layer in Haikou city as an example. Firstly, based on the analysis of the disturbance mechanism of surrounding rock in multi-row pipe jacking construction, the principle that multi-row pipe jacking construction should give priority to excavate two pipe jacking tunnels which are far apart in turn was established. Secondly, taking the maximum ground settlement at the center of pipe jacking as the judgment index, the optimal scheme of the construction sequence of multi-row pipe jacking was determined. Finally, based on the field measured data, the relationship between the jacking force, the pressure of the palm surface, the average frictional resistance and the jacking process during the jacking process was analyzed, and summarized the experience of the site construction. The results show that: (1) it is better to give priority to construct two pipe jacking tunnels which are far apart in the construction order multi-row pipe jacking; (2)Based on the empirical method of surface subsidence, the maximum surface subsidence at the center of pipe jacking group can be used as the judgment index to determine the optimal jacking sequence; (3)Under the condition of “from the two sides to the middle”, the surrounding rock around the middle jacking pipe is greatly disturbed by the construction of the first jacking pipe, its jacking rate should be reduced on the basis of the first building jacking pipe, and the cutting rate of the cutter and the grouting pressure should be increased, so as to realize the continuous jacking construction. The results of this paper are of great reference value to the determination of the jacking parameters of multi-row pipes in the future.

1. Introduction
Reasonable setting of jacking parameters can effectively ensure the safety and efficiency of pipe jacking construction. Jacking parameters mainly include jacking force, friction resistance, palm surface pressure, jacking speed and axis control, etc. The jacking force directly affects the design of the back wall of the working well, the strength requirements of the pipe joints, the number and spacing of relays, and the selection of jacking equipment. Besides, the influence of multiple pipe jacking sequences on the disturbance of surrounding rock soil should also be considered in the construction of multi-row pipe jacking.
In view of this, many scholars [1~3] have conducted a large number of studies on the jacking parameters of single-row jacking pipe. However, the complex relationship among axial deviation, grouting technology and frictional resistance cause it is hard to determine conditions for the selection of jacking parameters. Empirical formulas are widely used to calculate jacking parameters in practical projects [4-5]. Although they are simple and clear, most empirical formulas are only applicable to specific conditions, such as certain soil quality, certain pipe diameter range, jacking distance, etc. Therefore, for specific projects, the jacking parameters still need to be determined by combining field test and theoretical analysis.

The disturbance influence of jacking parameters on construction and the applicability of relevant empirical formulas has been studied by several scholars by means of numerical simulation, model test and field monitoring [6-10]. Li F B [6] established a Three-Dimensional finite element model of pipe jacking by using ANSYS software, and researched the stress and strain cases of the earth surface of the pipe jacking machine head under different pressure of the palm during the jacking process. Huang H W [7] use three-dimensional finite element method to simulate the combined action of pressure on the palm surface of pipe jacking machine, soil loss, grouting layer friction resistance and other factors, and studied the mechanical effects generated during pipe jacking construction. Ji X B [8] established a numerical model to analyze the relationship between pipe jacking force and frictional resistance under the condition of considering grouting lubrication. G.W.E.Milligan and P.Norris [9] carried out the pipe jacking model test and they studied the action mechanism of pipe soil and predicted the jacking force. Marco Barla[10] monitored and analyzed the jacking forces of multiple jacking segments at the site, on the basis of the research on the single pipe jacking. The results show that the measured results in the initial section of each jacking section are in good agreement with the predicted jacking force, but the predicted values in the latter section are all lower than the measured ones. The reason for this phenomenon is that the calculation model of jacking force does not consider the soil disturbance between pipes.

Hence, reasonable selection of jacking construction sequence and jacking parameters play an important role in the in-turn jacking construction of multiple rows of parallel pipe jacking with small spacing. Because of the large disturbance degree of soil between pipes and multiple disturbance during the pipe jacking construction process. However, restricted by the engineering practice, there are few studies on the optimization of jacking sequence and the setting of jacking parameters of multi-row jacking pipes in open literature data. So that, it is difficult to find relevant experience for multi-row pipe jacking construction.

To solve this problem, this paper based on the multi-row parallel pipe jacking project of haikou water-rich sand layer, establishes the optimization principle of multi-row pipe jacking construction sequence through the disturbance analysis of surrounding rock in multi-row pipe jacking construction. Based on the empirical formula of earth surface settlement method, the maximum surface settlement is used as the discriminant index to optimize the sequence of jacking construction. Finally, by means of field measurement, the relationship between the average friction resistance, the Jacking force, palm pressure and the jacking path is analyzed in in-turn jacking construction process, summarized the setting of jacking parameters and the experience of jacking. The job is expected to have reference value for future similar projects.

2. Project background
This project is the external drainage project of the 2nd expansion site of Haikou Meilan International Airport, which located in Meilan District, Haikou City, Hainan Province, China. The main line mileage of the project 4+776.3~5+435.9 (6#well~7#well) uses the three-hole horizontal diameter 3.5m jacking pipes(Figure 1), the transverse spacing of the jacking pipes is 3.18m, and the pipe circumference adopts special reinforced concrete pipes which length is 2.5m. The concrete strength grade is C50, and the impermeability grade is P8. The landform unit of the volcanic platform where the project is located. The main lithology is silty clay, strong and moderately weathered basalt, coarse sand, and bioclastic sand. The line mileage 4+776.3~5+435.9 (6#well~7#well) is part of the
horizontal three-row pipe jacking section. The representative section is shown in Figure 2. This section is composed of \( \text{⑦} \) layer of silty clay (6.3 \( \sim \) 16.2m) and layer \( \text{⑧} \) coarse sand (4 \( \sim \) 6.3m) as the foundation bearing layer, and the buried depth of the parallel jacking pipe is 4.62 \( \sim \) 8.76m.

3. Research on Construction Sequence of Multi-row Pipe Jacking
The selection of the pipe jacking machine is an important part of the pipe jacking construction design. Choosing a reasonable pipe jacking machine can avoid unnecessary construction risks, improve the construction schedule, and save construction costs[11]. According to the geological survey report of the supporting project, well section 6# \( \sim \) 7# mainly pass through silty clay and coarse sand, the
formation permeability is large, and the groundwater pressure is relatively high. Therefore, this project uses a mud-water balance pipe jacking, as shown in Figure 3.

![Figure 3. Large cutter disc slurry balanced pipe-jacking machine.](image)

### 3.1. Method for determining jacking sequence of multi-row jacking pipes

In order to determine the construction sequence of multi-row pipe jacking, according to the mutual disturbance mechanism of adjacent pipe jacking, the distribution of the soil lateral disturbance zone caused by the construction of three rows of parallel pipe jacking is shown in Figure 4. In the figure, $h$ is the buried depth of the pipe axis, $B$ is the horizontal distance between the two pipe jacks, $R$ is the radius of the shear disturbance zone, and $r$ is the outer radius of the pipe. According to the experience of multi-row pipe jacking research on surface settlement [12-14]: when the two pipe jacking axes are far apart, the first pipe jacking has no effect on the later pipe jacking; as the pipe jacking axis distance becomes smaller ($B > h + r$), disturb the soil on the side of the rear jacking pipe close to the first jacking pipe, and the relative influence is not big; when the distance between the two jacking pipe axes is close ($B < h + r$), the first jacking pipe is opposite to the back The disturbance of the jacking pipe has a greater impact.

Therefore, in multi-row pipe jacking construction, priority should be given to digging two pipe jacking tunnels that are far apart in sequence, so that the rear pipe jacking is far away from the soil lateral disturbance area caused by the first pipe jacking, thereby reducing the first pipe jacking to the later pipe jacking Impact. Since the surrounding rock in the middle of the pipe jacking construction has been subjected to double disturbances, the surrounding rock will be compressed and compacted. It is necessary to further analyze the characteristics of the surrounding rock after the disturbance to ensure the tunnel face pressure and jacking during jacking construction. Reasonable setting of rate.

![Figure 4. Schematic diagram of lateral disturbance of three rows of parallel pipe jacking.](image)

In order to further quantify the influence of the construction sequence of multiple rows of pipe jacking on the surrounding rock disturbance, based on the research of Wei Gang et al.[15-17], the
maximum surface settlement is used as the judgment index to determine the reasonable jacking construction sequence. The specific calculation steps are:

1. Find the disturbance edge point A of the first jacking pipe. The distance to the axis of the rear jacking pipe is approximately \( l_1 = h + r - B \);

2. According to the calculation method of the ground settlement of the first jacking pipe, let the soil loss per unit length be \( V_{f1} \) and the width coefficient of settlement trough is \( i_1 \), and the ground at point A can be obtained by the Peck formula. The settlement value is \( S_1 \);

3. The amount of soil loss caused by the jacking pipe after estimation is \( V_2 \) \( (V_2 > V_{f1}) \). Assuming that \( V_2 = V_{f2} \), \( i \) is unchanged, let the settlement value calculated by the Peck formula equal to the distance from the axis of point C as;

4. The maximum ground settlement value deviates from the axis by \( l \), \( l = l_2 - l_1 \), the soil is disturbed by the jacking pipe first, then The width of the ground settlement trough caused by the jacking pipe becomes larger. Assuming that the total width of the ground settlement trough is 6 times the width coefficient of the settlement trough \( 3i_2 = 3i_1 + l \), it can be obtained \( l_2 \);

5. From the formula \( S_i = \frac{V_{ij}}{\sqrt{2\pi}} \exp \left( -\frac{l_j^2}{2i_j^2} \right) \), the actual soil loss is calculated as \( V_{fj} \). If it is \( V_{fj} \) and \( V_2 \) larger, it should be adjusted \( V_{fj} \) and recalculated to \( V_2 \) obtain the approximate one \( V_{fj} \);

6. The same can be obtained, \( V_j \), \( i_3 \) and \( S_3 \), finally, the ground subsidence of the three rows of pipe jacks can be superimposed to obtain the final ground subsidence of the parallel pipe jacks.

3.2. Analysis and determination of jacking sequence

The actual site uses reinforced concrete circular pipes with an inner diameter of 3500mm and a wall thickness of 320mm. The pipe jack axis distance is 7.32m, the pipe axis depth is 10.71m, and the pipe outer radius is 2.07m. Taking the axis of the drive two as the o point, the Peck formula is \( S = S_{max} e^{-\frac{x^2}{2\pi}} \) used to calculate the cumulative ground settlement value of the three jacking pipes \( S_o \) at the o point. The final settlement value of the center point o is calculated and compared in the following according to different jacking sequences.

1. Jacking sequence "1-2-3": The settlement of drive 1 is calculated according to the first construction of the pipe jacking, the soil loss rate is calculated at 4%, and the ground settlement trough width coefficient is calculated \( i_1 = 0.43h + 1.1 = 5.71 \). The amount of soil loss per unit length \( V_1 = 0.04 \pi r^2 = 0.538 m^3 / m \), Maximum settlement value \( S_{max} = V_1 / \sqrt{2\pi i_1} = 0.038m \). The drive 2 is calculated according to the post-construction pipe jacking, the soil loss rate is calculated at 5%, and the soil loss per unit length is calculated \( V_2 = 0.67 m^3 / m \). The distance between the maximum ground settlement value and the axis is 1.09m, adjust the ground width coefficient of settlement trough \( 3i_2 = 3i_1 + l \), \( i_2 = 6.07 \), Maximum settlement value \( S_{max} = V_2 / \sqrt{2\pi i_2} = 0.044m \). The drive 3 is calculated according to the final construction pipe jacking, the soil loss rate is calculated at 5.5%, the soil loss per unit length \( V_3 = 0.74 m^3 / m \), the calculated maximum ground settlement value deviates from the axis of 0.93m, adjust the width coefficient of the ground settlement trough \( i_3 = 6.38 \), Maximum settlement value \( S_{max} = 0.046m \). The superposition results in the final settlement of the center point o as \( S_o = 0.085m \).
(2) Jacking sequence "1-3-2": The settlement of drive 1 is calculated according to the first construction of the pipe jacking, the soil loss rate is calculated at 4%, and the ground settlement trough width coefficient is \(i_1=5.71\). The amount of soil loss per unit length \(V_1=0.538m^3/m\), Maximum settlement value \(S_{1_{\text{max}}}=0.038m\). Drive 3 is calculated according to the post-construction jacking pipe. Since the axis of the rear jacking pipe is outside the disturbance zone caused by the first jacking pipe, the ground settlement is not affected by the disturbance of the first jacking pipe. Therefore, the soil loss rate is calculated as 4%, unit Length of soil loss \(V_3=0.538m^3/m\), \(i_3=5.71\) , Maximum settlement value \(S_{3_{\text{max}}}=0.038m\). Drive 2 is calculated according to the final construction jacking pipe, the soil loss rate is calculated at 5.5%, the soil loss per unit length \(V_2=0.74m^3/m\), the calculated maximum ground settlement value deviates from the axis 1.63m, adjust the ground width coefficient of settlement trough \(i_2=6.27\) , Maximum settlement value \(S_{2_{\text{max}}}=0.046m\). The superposition results in the final settlement of the center point \(o=0.079m\).

(3) Jacking sequence "2-1-3": The settlement of drive 2 is calculated according to the first construction of the pipe jacking, the soil loss rate is calculated at 4%, and width coefficient of settlement trough is \(i_2=5.71\). The amount of soil loss per unit length \(V_2=0.538m^3/m\), Maximum settlement value \(S_{2_{\text{max}}}=0.038m\). Drive 1 is calculated according to the post-construction pipe jacking, the soil loss rate is calculated at 5%, the soil loss per unit length \(V_1=0.67m^3/m\), the calculated maximum ground settlement value deviates from the axis 1.09m, adjust the ground width coefficient of settlement trough \(i_1=6.07\) , Maximum settlement value \(S_{1_{\text{max}}}=0.044m\). The drive 3 is calculated according to the final construction pipe jacking, the soil loss rate is calculated at 5%, the soil loss per unit length \(V_3=0.67m^3/m\), the calculated maximum ground settlement value deviates from the axis 1.09m, adjust the ground width coefficient of settlement trough \(i_3=6.07\) , Maximum settlement value \(S_{3_{\text{max}}}=0.044m\). The superposition results in the final settlement of the center point \(o=0.081m\).

The main settlement parameters of different jacking sequences are shown in Table 1:

| Construction sequence | Maximum settlement caused by post-construction pipe(m) | Adjust the width coefficient of settlement trough | Settling value at point o(m) |
|------------------------|-------------------------------------------------------|--------------------------------------------------|-----------------------------|
| "1-2-3"                | \(S_{1_{\text{max}}}=0.046\)                           | \(i_1=6.38\)                                    | \(S_o=0.085\)               |
| "1-3-2"                | \(S_{2_{\text{max}}}=0.046\)                           | \(i_2=6.27\)                                    | \(S_o=0.079\)               |
| "2-1-3"                | \(S_{3_{\text{max}}}=0.044\)                           | \(i_3=6.07\)                                    | \(S_o=0.081\)               |

It can be seen from the table that the settlement value of point o is the smallest when the jacking sequence is "1-3-2". Therefore, from the perspective of controlling ground settlement, the ground settlement caused by the "1-3-2" sequence of construction is the smallest, while considering the impact of actual construction, the theoretical calculation results will be amplified. Therefore, the "1-3-2" pipe jacking sequence will be adopted for the best on-site construction process.

4. Jacking parameters measured analysis

In order to summarize the change law of the jacking parameters during the jacking process of multi-row jacking pipes, we monitored the jacking force and tunnel face pressure of the tunnel face on the project site [18~20]. During the jacking process, the working pressure of the main jacking cylinder corresponding to each section of the jacking pipe is recorded in real-time, and the total pressure is
obtained according to the sum of the number of cylinders. The product of the full pressure and the area of the nose is the jacking force, which is converted into the total jacking force into the construction nose. It is difficult to measure the friction resistance directly. According to the principle that the total jacking force of the balance of forces is composed of the tunnel face pressure of the face and the friction resistance around the tube (Figure 5), when the tunnel face pressure of the face is known, the average friction resistance around the tube can be calculated by formula (1) [21].

\[
P_f = \frac{(F - P_d)}{\pi DL}
\]

Where \(F\) is Jacking force; \(P_d\) is Tunnel face pressure; \(P_f\) is Tube friction resistance; \(D\) is the direct pipe jacking; \(L\) is the length of the pipe jacking into the soil.

\[\begin{align*}
\text{Figure 5. The composition model of the total jacking force of the pipe jacking.}
\end{align*}\]

In order to reduce the impact of construction parameter fluctuations on data analysis, the average value of total jacking force, tunnel face pressure, and friction resistance per unit length (2.5 meters) of the pipe section is used and analyzed [22]. When the excavation of the pipe jacking has little change, the tunnel face pressure tends to be a constant value. In order to ignore the impact of the tunnel face pressure, the slope of the linear fitting curve of the total jacking force data is used to calculate the friction resistance of the pipe jacking per unit length.

According to the on-site construction sequence, drive 1 is jacked in from well 6# to well 7#. The relationship curve of total jacking force, average friction resistance, and jacking distance are shown in Figure 6.

\[\begin{align*}
\text{Figure 6. Variation of jacking force and Friction resistance during tunneling at drive 1.}
\end{align*}\]

It can be seen from Figure 6 that the jacking frontal resistance of the drive 1 is 2150kN. As the jacking distance increases, the jacking force shows an upward trend of oscillation, and the oscillation frequency is relatively uniform. The entire jacking force curve is divided into three sections according to the oscillation trend. In the 0–85m section, the jacking force showed a significant increase (up to 5670kN), and the following 85–490m section jacking force was basically maintained at 9072kN and
oscillated gently and slightly. After 490m, the shaking intensified. When the jacking distance reached 620m, the jacking force reaches the maximum value of 16380kN. The initial average frictional resistance of the drive 1 is 6.43kPa. It oscillates violently in the 0–85m section. It reaches the maximum value of 7.38kPa at 30m and then rapidly drops to 1.85kPa at 85m. After 85m, it slowly drops and stabilizes. It oscillated slightly near 1.61kPa.

After the construction of drive 1 is completed, the drive 3 is jacked from well 6# to well 7#. The relationship between total jacking force, average friction resistance and jacking distance is shown in Figure 7. It can be seen from Figure 7 that the frontal resistance of the drive 3 is 2150kN. With the increase of the jacking length, the jacking force shows an intermittently oscillating upward trend. The entire jacking force curve can be divided into 3 segments according to its trend. Between the 0–100m section, jacking force showed a substantial increase (up to 7560kN), and it jumped to 8316kN at 110m. The jacking force at the 110–530m section basically remained below 11090kN, and oscillated slightly. After 530 m, the turbulence intensified. When the jacking distance reached 600m, the jacking force reaches the maximum value of 14490kN. The initial average friction resistance of the drive 3 is 13.16kPa, and the oscillation is more severe in the 0-100m section. The average friction resistance reaching the maximum value of 23.98kPa at 13m and rapidly dropping to 3.07kPa at 98m. After 100m, it oscillates up and down slightly and slowly decreases until the curve flattens out, with only a small oscillation around 1.26kPa.

Figure 7. Variation of jacking force and Friction resistance during tunneling at drive 3.

Figure 8. Variation of jacking force and Friction resistance during tunneling at drive 2.
After the construction of drive 3 is completed, continue to jack drive 2 from well 6# to well 7#. When the drive 2 was jacked on site, we found that the jacking force changed greatly during the initial trial jacking stage. It is caused by multiple disturbances in the surrounding rock and soil around drive 2, so it needs to be appropriately reduced jacking speed by about 10%.

The graph of the relationship between total jacking force, average frictional resistance, and jacking distance is shown in Figure 8. It can be seen from Figure 8 that the frontal resistance of the drive 2 is 2150kN. With the increase of jacking distance, the jacking force shows an intermittently oscillating upward trend. The entire jacking force curve can be divided into 3 sections according to the trend, between 0~70m section jacking force showed a substantial increase (up to 6804kN), and the subsequent 70-330m section jacking force was basically maintained at 8316kN and oscillated gently and slightly. The jacking force jumped to 11090kN at 340m, and the jacking force at 340~640m. The jacking force is basically maintained at 11590kN and oscillates gently and slightly, reaching the maximum value of 13100kN at 605m. The initial average frictional resistance of the drive 2 is 10.23kPa, and the vibration is more severe in the 0~90m section, reaching the maximum value of 12.08kPa at 20m, and rapidly dropping to 2.68kPa at 90m. After 90m, it slowly decreases and stabilizes. There is a small oscillation around 1.15kPa.

A comparative analysis of the changing laws of the three pipe jacks' jacking force found that: (1)The jacking force of each pipe jacking tends to increase in the initial stage rapidly, the vibration is relatively severe, and the first peak occurs. As the jacking distance increases, the jacking force shows an overall increasing trend, but the trend is more violent, with a larger amplitude and higher frequency. The reason for this phenomenon is that in order to control the pipe jacking posture during the jacking construction process, the grouting pressure and the nose cylinder are repeatedly corrected during the construction process, resulting in a large change in the friction resistance of the pipe jacking pipe wall, so the jacking force is generated. Oscillation; (2)The maximum jacking force does not appear when the jacking distance is the largest, but at a certain stage after the jacking distance. The specific position is 615~625m from the jacking distance. This is because the pipe jacking machine is about to arrive In well 7#, the slowdown of jacking speed affects the fluctuation of jacking force value. (3)When the jacking sequence is "1-3-2", the maximum jacking force of drive 2 is obviously smaller than that of drive 1 and drive 3. The reason is that during construction, the jacking speed of drive 2 is reduced to ensure that the pipe jacking can be tunneled safely and smoothly.

A comparative analysis of the three jacking pipes average frictional resistance found that: (1)The average frictional resistance of the three-section jacking pipe was relatively large in the initial stage and oscillated severely, especially for the drive 3, which could reach a maximum of 23~24kPa. It is caused by factors such as the failure to form a complete mud sleeve at the initial stage of jacking and the unstable axis control. The hole of the wall of the drive 3 is unstable in the initial stage, so it is compared with the initial average friction resistance is higher than that of the drive 1 and the drive 2. (2)With the significant dilution effect of the jacking distance, the construction tends to be stable, the average friction resistance drops rapidly and tends to be stable, and only fluctuates slightly around 1.5kPa. This is because the mud sleeve has been formed intact and has good drag reduction performance, which can control the average friction resistance of multiple rows of jacking pipes.

| Jacking pipe number | Jacking path(m) | Maximum jacking force(kN) | Maximum average friction(kPa) | Average jacking force(kN/m) |
|---------------------|----------------|---------------------------|-------------------------------|-----------------------------|
| Drive 1             | 0~85           | 5670                      | 7.38                          | 31                          |
| Drive 3             | 0~100          | 7560                      | 23.98                         | 35                          |
| Drive 2             | 0~70           | 6804                      | 12.08                         | 75                          |
Table 3. Jacking force parameters of three-section pipe jacking at the middle stage.

| Jacking pipe number | Jacking path(m) | Maximum jacking force(kN) | Maximum average friction(kPa) | Average jacking force(kN/m) |
|---------------------|-----------------|---------------------------|-------------------------------|----------------------------|
| Drive 1             | 85~490          | 9072                      | 1.85                          | 9                          |
| Drive 3             | 110~530         | 11090                     | 3.07                          | 16                         |
| Drive 2             | 70~330          | 8316                      | 2.68                          | 14                         |

Table 4. Jacking force parameters of three-section pipe jacking at the final stage.

| Jacking pipe number | Jacking path(m) | Maximum jacking force(kN) | Maximum average friction(kPa) | Average jacking force(kN/m) |
|---------------------|-----------------|---------------------------|-------------------------------|----------------------------|
| Drive 1             | 490~640         | 16380                     | 1.61                          | 36                         |
| Drive 3             | 530~640         | 14490                     | 1.26                          | 23                         |
| Drive 2             | 330~640         | 13100                     | 1.15                          | 1.6                        |

Combining the above analysis with the on-site construction experience, the following three points should be paid attention to for the setting of long-distance multi-row jacking parameters:

1. Since it is difficult for the wall-protecting mud to fully exert its drag reduction effect in the jacking initial stage. Therefore it should be reduced the jacking rate and increase the grouting pressure in the jacking initial stage, so that to make the slurry fully diffuse and accelerate the formation of the overall mud jacket.

2. Due to the multiple corrections of the jacking posture during the jacking process, the jacking force changes show obvious segmentation. Therefore, during the jacking construction, it is necessary to pay attention to the axis deviation of the jacking pipe and the drag reduction slurry density so that to prevent the rise or sink of the pipe jacking process.

3. For multi-row jacking pipes, in order to achieve continuous jacking construction, it is necessary to appropriately reduce the jacking rate, increase the cutter head cutting rate, increase the grouting pressure, and reduce the face pressure when the middle jacking pipe is jacked. It is also possible to increase the design value of its pushing force during the design stage.

5. Conclusions

In order to determine the sequence and parameters of multi-row pipe jacking in water-rich sand layer reasonably, this paper established the multi-row pipe jacking in sequence on the basis of the analyzing of disturbance mechanism of surrounding rock in multi-row pipe jacking construction. Secondly, based on the empirical formula of earthsurface settlement, compared the maximum surface settlement at the center of drive 2 in different construction sequences, and the optimal scheme of the construction sequence of pipe jacking in multiple rows is determined. At last, the relationship between jacking force, palm surface pressure, average frictional resistance and jacking process is studied by means of field measurement, and summarized the experience of field construction. The main conclusions are as follows:

1. The principle of sequence optimization gives priority to the construction of two pipe jacking tunnels that are far apart. It can be calculated that when the jacking sequence is "1-3-2", the settlement value at the center point o is the minimum, thus the "1-3-2" order should be adopted for the sequential jacking sequence of multiple rows of jacking pipes.

2. The thrust force and the average frictional resistance in the process of site jacking were monitored. It is found that the jacking force of each pipe presents data oscillation, and the amplitude and frequency of oscillation are discrepant in different stages. When the jacking pipe is about to reach the receiving well, the jacking rate gradually slows down, and then the maximum jacking force appears in the jacking path. The jacking speed of drive 2 was reduced in the initial stage of construction, resulting in a smaller maximum jacking force of drive 2.
(3) When the jacking order of multiple rows pipe jacking is "from both sides to the middle", the construction of both sides of pipe jacking will cause great disturbance to the surrounding rock soil around the middle pipe jacking. This problem can be solved by adjusting the jacking parameters of the subsequent build jacking pipe based on the parameters of the already build jacking pipes. Specifically, reduce the jacking rate and increase the cutting rate and grouting pressure of the cutter. Based on this way, the later construction of pipe jacking can be successfully completed, and achieve continuous pipe jacking construction.

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