Numerical Simulation Analysis of Supporting Stability of Cast-in-place Piles in Pipe Jacking

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Abstract. Combined with the support excavation and pipe jacking construction of the pipe jacking working well in a section of Zhenjiang sponge city plan construction, the three-dimensional numerical analysis model was established by MIDAS-GTS, and the deformation of the supporting structure at each construction stage was analyzed. The conclusions are as follows: when the three-dimensional numerical analysis model is established, the deformation of the beam element is closer to the real situation than that of the plate element beam element; in the process of pipe jacking construction, the displacement of the supporting structure is opposite to that of the jacking direction after the Jack loads, and the displacement trend changes linearly with the magnitude of the Jack force. in the process of pipe jacking construction, the maximum displacement of the supporting pile occurs at the break of the supporting pile at the exit of the pipe jacking machine. the deformation of the supporting pile can be effectively reduced by strengthening the soil in a certain range of the opening of the pipe jacking. Through the simulation analysis of excavation support and subsequent pipe-jacking construction with concrete cast-in-place pile, the results can provide a reference for the design of supporting structure and the control of surface subsidence and deformation during construction.

1. Introduction
In recent years, with the vigorous development of the national public infrastructure and the proposal of the sponge city plan, the construction of the pipe jacking method has been widely applied to actual engineering construction because it does not damage the environment or affect transportation, and has low construction cost and high social benefits. However, the stability of the working well in the pipe jacking construction is an important prerequisite for the construction work and the most basic requirements for normal construction. The selection and safety of the supporting form of the pipe jacking work not only affects the safety, schedule and cost of the entire project, but also has an important impact on the quality of the entire pipe jacking construction[1]. The structure design of the working well and the design of the support system must not only ensure that the foundation pit excavation does not produce large deformation, but also maintain stability during the jacking process of the jacking pipe, and can not produce a large horizontal displacement to avoid affecting the top. Pipe construction quality. Previous scholars have done the following research on the stability of working wells;Gong ci et al put forward a new method for calculating allowable reaction force in rectangular caisson working well by studying and analyzing the earth pressure of back wall. This method assumes that the back wall of the caisson is deformed into parabola shape under the action of pipe jacking, and the soil under zero displacement is compressed but not in a passive state. The earth

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pressure related to displacement is calculated for the soil under pressure. At the same time, friction resistance of side wall and bottom of caisson is considered [2]. Xu Huifen and others studied the space-time deformation characteristics of the working well and surrounding soil by establishing a three-dimensional finite element stratigraphic structure model, considering the interaction between soil and structure, and studied the soil reinforcement scheme. In order to ensure the overall stability of the working well during the later construction process, reduce the impact on the ground subsidence caused by the construction. Qing yisong et al took the protection of bridge abutment by bored pile and cement mixing pile as the engineering background and introduced the successful application of bored pile and cement mixing pile in pipe jacking working well support. This paper introduces the design, calculation process and construction technology of bored pile and cement mixing pile [4]. Li Zhongmin and others took the successful construction case of the Longquan River comprehensive treatment project in Jimo City, this paper introduces that the working well supported by steel sheet pile can ensure the stability and safety of the working well in the process of pipe jacking by controlling the large length of jacking and setting the working well and checking well [5]. Wang Donghui and others considering the project cost and construction scale, put forward adopting the detachable support type working pit to ensure the smooth construction of pipe jacking and to provide reliable jacking counterforce fulcrum for pipe jacking construction through force transfer device and special material plate wall [6]. Previous scholars have not considered the deformation of support structure caused by pipe jacking construction and the ground subsidence caused by deformation of supporting structure, whether for caisson structure or other forms of support.

Based on the excavation construction and pipe jacking construction of a pipe-jacking working well in Zhenjiang City, a three-dimensional numerical analysis model is established by using MIDAS-GTS software to simulate the force change of the supporting structure during the whole construction process. And the surface subsidence deformation analysis.

2. Engineering background

2.1. Project Overview

The project is located in the green bamboo lane area of Jinshanhu nan bank of Zhenjiang city and is one of the construction projects of the sponge city in Zhenjiang city. The purpose of the project is to solve the drainage and water logging problem of Huashan Bay Square and Green Bamboo Lane entrance in the green bamboo lane area. The pipe-jacking working well is located in the west side of the urban traffic road. The actual location of the working well is shown in Figure 1.

![Figure 1. Working well construction location](image1)

2.2. Engineering Geology and Hydrological Conditions

2.2.1. Engineering Geology. According to the geological survey report, the construction of working well support and excavation involves the condition of soil layer and the layer thickness as follows:
1-1 Miscellaneous fill: gray-brown-grey-blue, slightly wet, densely structured, mainly for pavement layer or block, etc., and the accumulation time is about 3 to 10 years. The layer thickness is 0.5 meters.

1-3 Plain fill: gray-blue - gray brown - variegated, saturated, loose structure, soft plastic - flow plastic state, the main component is silty clay or soft plastic state silty clay with more gravel, block Stones, broken bricks, etc., the size of the crushed stone varies from 3 to 20 cm, the cementation is poor, the hard impurity content is about 35 to 55%, and the accumulation time is about 3 to 10 years. The layer thickness is 2.4 meters.

3-1 Silty clay: taupe, saturated, fluid-plastic state, localized with a small amount of silt or silt, medium dry strength, low toughness, dull, high compressibility. The layer thickness is 1.1 meters.

3-t Silt: gray-blue, saturated, slightly dense, mainly containing a large amount of mica fragments or a small amount of silt. The mineral components are mainly quartz and feldspar. The particles are round-sub-circular and have poor gradation. The diameter is 0.075-0.25 mm, accounting for 52.3%, 0.005-0.075 mm, accounting for 41.4%, and less than 0.005 mm, accounting for 6.3%, low dry strength, no toughness, dullness, obvious shaking reaction, and moderate compressibility. The layer thickness is 1.4 meters.

5-1 Silty clay: grayish yellow, saturated, plastic state, containing a small amount of manganese core, medium dry strength, medium toughness, luster, no shaking reaction, medium compressibility. The layer thickness is 5.2 meters.

5-2 Silty clay: yellow-brown, saturated, hard plastic state, with more manganese core, medium dry strength, medium toughness, luster, no shaking reaction, medium compressibility. The layer thickness is 19.4 meters.

2.2.2. Groundwater conditions at the site. The main types of groundwater affecting the project are diving and micro-bearing pressurized water. Diving is mainly found in the 1-1, 1-2, 1-3, 3-1, 3-t strata. The soil of the 1-1, 1-2, and 1-3 layers is loose, and the amount of water produced during the rainy season is relatively large. The 3-t layer is a strong permeable layer, and the 3-1 layer is a weak permeable ~ micropermeable layer. The submersible water layer mainly accepts the recharge of atmospheric precipitation, and the excretion method is natural evaporation and lateral runoff. During the survey, the depth of water level was measured at 1.80 to 4.12 meters, the depth of stable water level was 1.05 to 1.71 meters, and the annual variation of water level was 0.50 to 1.50 meters. The micro-confined water is located in the 4-1 and 4-2 layers of silt and is a strong permeable water layer. Its depth of water level is basically the same as that of diving. The microbearing water layer is not involved in the excavation of the working well, and the precipitation scheme is designed with tube well precipitation.

2.3. Project Difficulties
In the later stage of working well support excavation, it serves pipe jacking construction. The construction cycle of pipe jacking is longer, and the construction site is narrow, which requires that the construction process cannot affect the normal traffic, and the pipe network around the site is vertical and horizontal. The complex environment requires strict control of surface subsidence and deformation.

2.4. Working well structure and support method
The working well is a cast-in-place reinforced concrete structure, with a length of 7 m, a width of 5 m, a wall thickness of 0.7 m, a working well floor top elevation of -0.268 m, a floor thickness of 0.7 m, a cushion thickness of 0.1 m, a pit bottom elevation of -2.53 m, and a site leveling 6.30 m. The excavation depth is 8.83 m.

The excavation and support scheme of the working well is as follows: a reinforced concrete waist beam is used to support the crown beam of bored cast-in-place pile, and a double pipe high pressure jet grouting pile waterproof curtain is set out outside the pit. Among them, the diameter of supporting
pile is 0.8m, the length of pile is 15m, the width of crown beam is 1.0 m, the height is 0.8m, the width of supporting waist beam is 0.6m, and the height is 0.7m.

3. Numerical Simulation Analysis of Excavation Support and Top Pipe Construction

3.1. Numerical analysis model

In this paper, the large-scale universal finite element software MIDAS-GTS is used to simulate the excavation of working well support and the construction of pipe jacking. According to the depth of foundation pit excavation and the influence range of excavation construction, a three-dimensional numerical analysis model of 50m in length, 40m in width and 50m in height is established. The effect of the model is as shown in Figure 2 below.

![Figure 2. Numerical analysis model](image)

The boundary around the model is set to limit the movement of the corresponding horizontal direction, the bottom surface of the model is set to restrict the horizontal and vertical movement, and the surface of the model is free. In addition to considering the weight of the model, the model applies the uniform load of 20KN/ to simulate the disturbance of the construction machinery. The boundary constraints of the model and the setting of the construction load are shown in Figure 2.b. In order to verify the reliability of the calculated results of the model, the results of the simulation analysis are compared with the results of the theoretical calculations.

3.2. Material parameters

In the simulation process, the soil is modeled by the Mohr Coulomb constitutive model, and the 3D solid element is used to simulate the situation of each layer. The mechanical parameters of the material are selected according to the mechanical properties provided by the geological survey report. The determination of the elastic modulus ES of each soil layer in the model is based on the engineering experience. The deformation modulus E0 value of the soil in the geological survey report is 3 to 5 times, and the simulation is taken 5 times. The concrete supporting and supporting structure adopts the elastic constitutive model, and the supporting piles are respectively analyzed by beam unit and plate unit. The material mechanics parameters, constitutive models, and unit type settings involved in the model are listed in Table 1 below.

| Name      | E (Mpa) | γ (KN/m³) | μ | φ (°) | C (Kpa) | Model constitutive | Unit type |
|-----------|---------|------------|---|-------|---------|-------------------|-----------|
| 1-3solum  | 37.2    | 18.7       | 0.33 | 6.5   | 38      | M-C              | Entity unit |
| 3-1solum  | 15.25   | 17.5       | 0.38 | 5     | 15      | M-C              | Entity unit |
| 3-tsolum  | 33.05   | 18.5       | 0.3  | 22    | 2       | M-C              | Entity unit |
In order to make the simulation closer to the actual construction, the pile interface contact was added to the support pile during the simulation. At the same time, support analysis is carried out on the support piles with equal stiffness substitution to the same stiffness. The cross section of the support structure and the specific settings of the contact interface are listed in Table 2.

### Table 2. Support structure cross section and contact parameters

| Name          | Kn  | Kt  | C  | φ  | D  | Remarks       |
|---------------|-----|-----|----|----|----|---------------|
| Pile interface| 600000 | 600000 | 50 | 23 | -  | -             |
| Supporting pile | -   | -   | -  | -  | 0.8 | beam          |
| Supporting pile | -   | -   | -  | -  | 0.62 | board        |
| Crown beam    | -   | -   | -  | -  | 1.0x0.8 | beam       |
| Ring beam     | -   | -   | -  | -  | 0.6x0.7 | beam       |

### 3.3. Simulation of working well excavation process

On the basis of site construction procedure, the scene construction environment is simulated by controlling unit life and death. The excavation of the foundation pit is divided into three steps: first, the supporting pile is constructed and the excavation depth is 1.4 m, the second step activates the excavation depth of the crown beam foundation pit, and the third step activates the ring beam foundation pit excavation to the bottom of the pit. Based on the deformation trend of supporting excavation this paper intercepts the analysis of the maximum deformation in the excavation process that is the third step when excavation to the pit bottom deformation cloud map. The maximum horizontal displacement of the supporting structure is shown in Figure 3 below.

![Figure 3. Horizontal displacement cloud diagram of the supporting structure of the foundation pit excavation](image-url)
3.4. Analysis of working well stability under top force

3.4.1. Work well numerical analysis model. Through comparison and analysis, it is found that beam element is more suitable for simulating excavation support structure of foundation pit, so beam element is used to simulate excavation support structure in this stage of numerical analysis model. According to the site construction sequence, after the foundation pit is excavated to the design elevation, the working well bottom plate and the inner wall are poured and the exit hole is pre-reinforced. Before the construction of the pipe jacking, the inner wall of the outlet and the supporting pile shall be broken. The structure of the working well in the simulation analysis is shown in Figure 5 below. The parameters and unit types of the inner wall of the working well and the reinforcement of the working hole in the model are listed in Table 3 below.
In this stage, in order to make the inner wall of working well closer to the real stress, a contact pair is set up after the completion of the construction of the working well to simulate the contact friction between the wall and soil, and the contact pair adopts the Mohr Coulomb friction interface. The friction coefficient is 0.577.

### 3.4.2. Analytical working conditions.

In this stage, the stability of supporting structure under the action of pipe jacking is considered in the numerical simulation. The main steps of the simulation are as follows: excavation of foundation pit with step by step, bottom slab of working well, pouring of inner wall, reinforcement of opening of pipe jacking; The hole wall and supporting pile are broken, and the top thrust of pipe jacking construction is loaded.

Because the maximum allowable force of the working well structure is less than the maximum allowable force of the pipeline, the maximum allowable force of the working well is the upper limit in the simulation process. In view of the actual construction situation simulation, the 80% allowable jacking force of the working well is loaded separately, and the maximum value of the designed top force is analyzed.

### 3.4.3. Simulation results.

The deformation cloud diagram of supporting structure and surface subsidence is shown in Figure 6 below.
a. Foundation pit excavation to the ground surface settlement deformation

b. 80% design bearing capacity surface settlement deformation

c. 100% design bearing capacity surface settlement deformation

d. 80% deformation of soil under design load capacity

e. 80% deformation of support piles under design load capacity
From Figure 6 above: a it can be seen that the maximum surface settlement deformation of the excavation of the foundation pit is -7.386 mm; B It can be seen that the maximum deformation value of surface settlement around the foundation pit caused by 80 % of the top pipe load to the allowed top force is -9.557 mm; C It can be seen that the maximum deformation value of surface settlement around the foundation pit caused by the loading of the top tube construction Jack to the maximum allowable top force is -9.779 mm. Analysis of e and f in Figure 6 reveals that the maximum deformation of the supporting structure occurs at the exit of the pipe jacking machine and the contact of the supporting pile, and the overall force of the supporting structure is greatly changed. With the trend of settlement deformation around the top loading of the top pipe, the maximum deformation of the retaining pile occurs at the exit of the pipe, and it also increases linearly with the top loading.

The supporting pile produces reverse displacement along the direction of pipe jacking under the action of pipe jacking. Because the displacement of the supporting structure is different due to the displacements of the asymmetric loading structure, the tendency of ground subsidence and deformation caused by the movement of the supporting structure is also different. In comparison with
Figure 7 a and b, it is found that the settlement deformation in the jacking direction is more obvious, which also highlights the importance of strengthening the tunnel opening of the pipe jacking machine.

4. Construction Plan Optimization and Site Construction Feedback

After the numerical simulation analysis of the whole construction process, taking into account the weak links of the supporting structure, some optimization measures have been taken on the construction plan as a whole:

1. The soil mass between piles is strengthened by high pressure spout pile, which makes the supporting pile become a whole structure.
2. Soil is strengthened by three axis cement soil mixing pile in order to reduce the influence of pipe jacking on surface settlement.
3. The construction of the working well was completed on July 10, 2018. During the pipe jacking construction in the working well, there was no deformation or mechanical damage affecting the normal construction, and the spot real-time monitoring did not exceed the warning value. Pipe jacking construction has been completed on November 15 of the same year acceptance.

5. Conclusion

In this paper, a three-dimensional numerical analysis model is established by using MIDAS-GTS to simulate and analyze the excavation and support construction of working well and the process of subsequent pipeline jacking construction. The results of analysis and study on the deformation of the model are as follows:

1. Considering the space effect of foundation pit supporting structure, it is more suitable to simulate working well support pile with beam element than with plate element in the simulation process.
2. The deformation of supporting structure changes linearly with the load of pipe jacking force.
3. The maximum displacement of supporting pile under the action of top force loading occurs at the exit of pipe jacking machine. Because the integrity of the broken supporting pile is destroyed, the force of supporting pile is similar to that of cantilever beam, and the free section produces large flexural deformation. In the process of construction, it is very necessary to take into account the safety of construction and surface deformation to reinforce the outlet of pipe-jacking machine.
4. According to the analysis of the structure of caisson with reference [7-9], the stability of the pile body embedded in the concrete cast-in-place pile is better because of the greater depth of the pile. Similar caisson structure will not move backward under the action of top force. On the contrary, the horizontal displacement of supporting pile during excavation is similar to that of prefabricated structure, which can counteract some of the deformation of supporting structure under the action of top thrust.

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