Research on Influnence Law of Existing pipe-jacking Tunnel affected by Adjacent Foundation Pit Excavation in Soft Clay Stratum

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Abstract. The problem that existing pipe-jacking tunnel was disturbed by adjacent foundation pit excavation had arose relative researcher’s attention, especially in soft clay stratum. Firstly, by means of numerical simulation, the deformation of diaphragm wall and settlement law of soil outside the pit during foundation pit construction were analyzed. Then deformation and stress characteristics of existing pipe-jacking tunnels were studied influenced by different spacing between foundation pit and pipe-jacking, different excavation depth of foundation pit and different buried depth of pipe-jacking. The main conclusions were as follows. (1) The maximum horizontal displacement of the diaphragm wall was located at 3/4 of the excavation depth of pit. (2) Due to the blocking or isolation effect of existing rigid pipe-jacking on the deformation of surrounding soil, the surface settlement became smaller. (3) Deformation, structural stress of pipe-jacking would gradually decreased under the conditions of increase of the spacing between foundation pit and pipe-jacking, decrease of excavation depth of pit and buried depth of pipe-jacking. (4) Due to the influence of pit excavation, deformation and stress of pipe-jacking near the end wall and middle of the foundation pit were relatively large. (5) When the buried depth of pipe-jacking was located at near 3/4 of excavation depth of pit and the spacing was less than 10m, excavation of the pit has a great impact on the existing pipe-jacking tunnel.

1. Introduction
Jacking pipe method had been applied in urban construction more and more widely since its trial development in 1896 in the United States. It had the characteristics of little impact on the surrounding environment, fast construction speed and less auxiliary work [1].

With the further development of urban underground space, a large number of engineering adjacent pipe-jacking tunnels had been constructed, which inevitably disturbed the adjacent pipe-jacking [2]. For foundation pit engineering, due to the large depth and wide scope of excavation, the impact on surrounding projects was more obvious. Especially in soft clay stratum, it was very sensitive to the nearby construction disturbance. Therefore, the disturbance control on pipe-jacking tunnel caused by foundation pit excavation in soft clay stratum had become a common problem in urban construction. Aimed at the proximity construction of pipe-jacking, some scholars and engineering technicians had carried out some researches. Wei Gang studied the deformation law of pipe-jacking tunnel while
underground pipeline crossing under the pipe by numerical simulation method\[3\]. Based on Shanghai Metro Line 8, Chen Peitai analyzed the deformation and damage of existing pipe-jacking during shield construction through on-site monitoring, and put forward deformation control measures\[2\]. By means of engineering monitoring and numerical simulation, Xie Xiongyao discussed the influence of foundation pit excavation on the underlying pipe-jacking tunnel, and put forward pertinent control measures\[4\]. Relying on Ningbo residential foundation pit excavation project, Song Wenxin analyzed the influence of foundation pit excavation on pipe-jacking tunnel, and considered that the deformation of tunnel presented the characteristics of big in the middle and small at both ends\[5\].

Because of the complexity of practical engineering and the uncertainty of geotechnical characteristics, it was difficult to directly use the research results of a single project, although they had reference significance for similar projects. At the same time, the influence of foundation pit excavation on pipe-jacking tunnel in soft clay area still had many undefined laws and unsolved problems. So numerical simulation was used to analyze the settlement characteristics of diaphragm wall and soil outside the foundation pit in soft clay stratum during pit digging. And the influence of foundation pit construction on deformation and stress of nearby pipe-jacking structure under different spatial positions were revealed. This would provide reference for similar engineering design and construction.

2. **Numerical Calculation Model**

2.1. *Simulated working conditions*

In order to clarify the relationship between foundation pit excavation and deformation of pipe-jacking, three influence factors were considered. They were spacing between tunnel and foundation pit, depth of foundation pit excavation and buried depth of tunnel.

The condition that 20m in pit depth($H$), 4m in net distance($d$) between pit and tunnel and 7m in tunnel buried depth($h$) were taken as benchmarks shown in Figure 1. The simulated working conditions were listed in Table 1.

![Figure 1. Position relationship between foundation pit and pipe-jacking](image)

| Surface | Foundation pit | Pipe Jacking | Diaphragm wall | Soil |
|---------|----------------|--------------|----------------|------|

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

2.2. *Numerical model*

For the benchmark working condition, the foundation pit had a length of 200 m, a width of 20 m and a excavation depth of 20 m. The pipe-jacking tunnel was a circular section with an outer diameter of 3.6 m and a wall thickness of 30 cm.

The retaining structure of foundation pit was C30 diaphragm wall with a thickness of 1 m and a vertical depth of 40 m. The depth of diaphragm wall embedded in bottom soil was 20 m. The internal horizontal brace were steel tube brace with a diameter of 0.47m. There were four layers of rigid brace with spacing 3.5m×3.0m. The material of pipe-jacking tunnel was C50 concrete.

Three-dimensional finite difference software was used to numerical calculation. The standard model
Table 1. Working conditions

| Numbering | Depth of foundation pit/m | Spacing/m | Burial depth of tunnel/m |
|-----------|---------------------------|-----------|-------------------------|
| 1         | 20                        | 2         | 7                       |
| 2         | 20                        | 3         | 3                       |
| 3         | 20                        | 4         | 4                       |
| 4         | 20                        | 10        | 7                       |
| 5         | 20                        | 15        | 7                       |
| 6         | 20                        | 20        | 7                       |
| 7         | 5                         | 3         | 3                       |
| 8         | 10                        | 4         | 4                       |
| 9         | 15                        | 7         | 7                       |
| 10        | 20                        | 10        | 10                      |

Table 2. Soil parameters of hardening soil small

| Parameters | ρ/kg·m⁻³ | c’/kPa | φ/° | K₀ | ψ/° | m | ρˢᵗ/skPa | νₑ | Eₛˢᵗ(ref)/MPa | Eₑₑ(ref)/MPa | Rᵣ | Gᵣ(ref)/MPa | γ₀/γ |
|------------|----------|--------|-----|----|-----|---|----------|----|----------------|----------------|----|------------|------|
| muddy clay | 1700     | 5      | 25  | 0.50 | 0.9 | 100 | 0.2      | 8 | 24             | 4              | 0.9 | 19.2       | 2.1×10⁴ |
| sandy clay | 1800     | 1      | 32  | 0.47 | 1.0 | 100 | 0.2      | 30 | 90             | 25             | 0.9 | 72         | 1.8×10⁴ |

Table 3. Physical and mechanical parameters of structure and materials

| Parameters         | Density ρ/(kg·m⁻³) | Elasticity modulus E/MPa | Poisson ratio ν | Section area/m² | Inertia moment about y-axis/m⁴ | Inertia moment about z-axis/m⁴ |
|--------------------|--------------------|--------------------------|----------------|-----------------|-----------------------------|-----------------------------|
| Pipe-jacking       | 2500               | 210×10³                   | 0.2            | —               | —                           | —                           |
| Diaphragm wall     | 2500               | 31×10³                    | 0.2            | —               | —                           | —                           |
| Brace              | 7850               | 210×10³                   | 0.3            | 0.1746          | 2.619×10³                   | 2.619×10³                  |

2.3. Selection of Constitutive Relations and calculation Parameters

Hardening Soil Small (HSS) model was adopted to simulate the soft soil. The muddy clay ranged from 0 to -25 m and sandy clay -25~-60m. The diaphragm wall was linear elastic constitutive model and simulated by liner element. The braces of foundation pit was elastic constitutive model and simulated by beam element. pipe-jacking tunnel was simulated by solid element complied with linear elastic constitutive model. Soil and structural parameters were used as shown in Table 2 and Table3.

2.4. Simulation of construction process

The simulation process was divided into two steps. (1) Jacking of pipe: It mainly included three key substeps. That were jacking of the pipe, applying the soil pressure on the working face, and generating of pipe segments and mud sleeves. (2) Excavation of foundation pit: the diaphragm wall was constructed before foundation pit excavation. The foundation pit was divided into seven layers to be...
constructed. The excavation depth was 0~1 m, -1~4.5 m, -4.5~8 m, -8~11 m, -11~14 m, -14~17 m and -17~20 m respectively. When each layer was excavated, the top brace of each layer was applied at the same time.

3. Analysis of calculation results

In order to study the influence of foundation pit excavation on pipe-jacking tunnel in soft clay layer, the horizontal deformation of diaphragm wall, settlement of soil outside the pit, stress and deformation of pipe-jacking tunnel different position relations were analyzed. The disturbance law under different engineering orientation conditions was revealed.

3.1. Horizontal deformation characteristics of diaphragm wall

Taking the diaphragm wall near the existing tunnel as the research object, the horizontal deformation variation along the vertical direction during the construction process were shown in figure 3.

The figure showed that: (1) During the construction of foundation pit, the horizontal deformation of diaphragm wall occurred in the direction of the inside of pit, and the deformation value increased with the increase of excavation depth. (2) With the increase of excavation depth, the maximum horizontal displacement position of diaphragm wall gradually moved downwards, and the final location was near 3/4 of excavation depth. (3) The maximum deformation of diaphragm wall was 29.2 mm.

3.2. Settlement law of soil outside foundation pit

3.2.1. Effect of spacing between pipe-jacking and foundation pit

The settlement nephogram of the soil outside the diaphragm wall after foundation pit excavation under 2m spacing was shown in Figure 4. And four monitoring lines of settlement were set at different depths (0m, -5m, -7m and -10.6m). The typical settlement curves under different spacing were shown in Figure 5 and Figure 6. Buried depth of tunnel was 7 m.

It can be drawn from calculation that: (1) The settlement decreased gradually from the surface downwards, and the maximum settlement position was about 10 meters outside the wall. (2) Existence of rigid pipe-jacking could block or isolate the settlement of soil around pipe. But the influence decreased gradually with the increase of the spacing between pipe-jacking and foundation pit. (3)
When the spacing was less than 10 m, the influence on soil settlement was significant; but while the spacing was more than 10m, the influence could be neglected.

3.2.2. Influence of excavation depth of foundation pit
When the depth of existing pipe-jacking was 7 m and the spacing was 4 m, the maximum settlement statistics of the different soil position under different pit excavation depth were shown in Table 4, and the typical settlement curve was shown in Figure 7.

The calculation showed that: (1) The depth of foundation pit had a significant effect on the settlement of the soil outside the pit. With the excavation depth increased, the settlement of soil and the influence range would become larger. (2) With the excavation depth increased, the distance of the maximum settlement position of the soil became farther from the foundation pit.

| Items                      | 0m  | -5m | -7m | -10.6m |
|----------------------------|-----|-----|-----|--------|
| Excavation depth of foundation pit |     |     |     |        |
| 5m                         | 0.3 | 0.1 | -   | -      |
| 10m                        | 0.5 | 0.3 | 0.1 | -      |
| 15m                        | 5   | 4.2 | 4   | 2      |
| 20m                        | 15  | 14  | 13  | 9      |

Figure 7. Settlement curves of soil outside foundation pit under 20m excavation depth

Figure 8. Settlement curve of soil under pipe buried depth of 3m

3.2.3. Influence of buried depth of pipe-jacking
The settlement curve of soil under different buried depth were shown in Figure 8 ~ Figure 10. With the increase of buried depth, surface settlement of the soil outside the pit increased gradually, and the maximum settlement position tended to gradually shift to the diaphragm wall, which was close to the state without pipe-jacking.

Figure 9. Settlement curve of soil under pipe buried depth of 5m

Figure 10. Settlement curve of soil under pipe buried depth of 10m

3.3. Deformation Law of Existing pipe-jacking

3.3.1. Effect of spacing between pipe-jacking and foundation pit
The deformation curves of pipe-jacking under different spacing were shown in Figure 11.

We can see from Figure 11 that: (1) Excavation disturbance degree on pipe-jacking was related to spacing. Large horizontal and vertical non-uniform deformation occurred along the pipe-jacking, and
the horizontal deformation was relatively larger. (2) The smaller the spacing, the larger the horizontal deformation of pipe-jacking structure. (3) The vertical deformation of pipe-jacking was more complex. When the spacing was less than 10m, the larger the spacing, the larger the vertical deformation of the structure. But when the spacing was more than 10m, the larger the spacing, the smaller the vertical deformation.

3.3.2. Influence of excavation depth of foundation pit
From above analysis, it can be seen that the horizontal deformation of pipe-jacking was relatively large caused by pit excavation. Therefore, the horizontal deformation of pipe-jacking under different excavation depth were shown in Figure 12.

It can be seen that when the excavation depth of the pit was less than buried depth of the pipe-jacking, the excavation of pit had less influence on the deformation of the pipe. When the depth of pit excavation was greater than the buried depth, the horizontal deformation of pipe increased with the increase of the depth of pit. And the phenomenon of uneven deformation became more and more obvious, thus disconnection of pipe-jacking joint became more serious.

3.3.3. Influence of pipe-jacking depth
Horizontal deformation of pipe-jacking under different buried depth of pipe was shown in Figure 13. It can be seen that with the increase of the buried depth of pipe, the horizontal deformation of the pipe increased gradually, and the horizontal inclination angle of pipe increased gradually. This was because the buried depth approached to 3/4 excavation depth of pit.

3.4. Stress of existing pipe-jacking

3.4.1. Influence of Spacing between pipe-jacking and foundation pit
Distribution of maximum principal stress and shear stress of pipe-jacking structures with different spacing were shown in Figure 14 and Figure 15.
It can be seen that: (1) With the increase of spacing, the maximum principal stress and shear stress of pipe-jacking gradually decreased, and the influence of pit construction on pipe-jacking was weakened. After 10 meters away, the pipe-jacking was no longer affected by pit excavation. (2) The distribution of the maximum principal stress along the pipeline showed that the maximum value appeared at 20m away from the end wall of the pit, with a value of 1.45 MPa. (3) The maximum shear stress of the structure mainly appeared at the corresponding end wall position, with a value of 1.6 MPa.

3.4.2. Influence of excavation depth of foundation pit

The stress of pipe-jacking under different excavation depth of foundation pit was shown in Figure 16 and Figure 17. It can be seen that: (1) With the increase of the excavation depth, the maximum principal stress and shear stress of pipe-jacking increased linearly (except 5 m of the excavation depth). (2) If buried depth of pipe was larger than the excavation depth of foundation pit, the excavation of pit had little influence on it. (3) The maximum principal stress of the pipe occurred at the pipe-jacking section 20m away from the end wall of the foundation pit, and the maximum shear stress occurred at the corresponding end wall position. (4) When the excavation depth of pit increased from 10 m to 20 m, the maximum principal stress and shear stress of the structure increased separately about 1.0 and 1.5 times. So shear stress of the structure was more sensitive to the excavation depth.

3.4.3. Influence of buried depth of pipe-jacking

The structural stress of pipe-jacking under different buried depth was shown in Figure 18 and Figure 19. It can be seen that with the increase of the buried depth of the pipe, structural stress gradually increased after the excavation of the foundation pit. This was mainly due to the fact that as the buried depth of the pipe increased, the closer the pipe was to the position of maximum deformation of diaphragm wall. This would lead to the larger horizontal displacement of pipe-jacking, which also could increase the stress of structure. The location of the maximum stress was consistent with those mentioned above.
4. Conclusion
In this paper, the deformation characteristics of diaphragm wall and the settlement law of soil outside the pit during excavation of foundation pit in soft soil were analyzed by numerical simulation. And the influence of pit excavation on deformation and stress of existing pipe-jacking under various working conditions was discussed. The main conclusions were as follows:

(1) The maximum horizontal displacement of diaphragm wall increased with the excavation depth of foundation pit increased. And its position also gradually moved downwards, and finally located at 3/4 of the excavation depth.

(2) Existing pipe-jacking would make the settlement of soil outside the pit become small. This was because that the rigid pipe would block or isolate the deformation of surrounding soil. But the influence decreased with the increase of the spacing between pipe-jacking and foundation pit. When the spacing was more than 10m, the influence could be neglected.

(3) Foundation pit excavation had significant influence on horizontal deformation of existing pipe-jacking. With the increase of the spacing, the decrease of excavation depth and buried depth of pipe, deformation of pipe-jacking decreased gradually.

(4) With the increase of the spacing, the decrease of the excavation depth of foundation pit and buried depth of pipe, the additional stress of pipe-jacking caused by foundation pit excavation decreased gradually.

(5) On the whole, when the buried depth of pipe-jacking was 3/4 of the excavation depth and the spacing was less than 10m, the excavation of the foundation pit had a great influence on the deformation and structural stress of the existing pipe-jacking tunnel. Particular attention should be paid to the state of the pipe-jacking structure near the end and middle of the foundation pit.

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