The Numerical Analysis of Tunnel Traversing Piles and Its Seismic Response in Deep Soft Soil

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Abstract. The Ou River estuary deposits deep soft silt and silt clay, the pipe-jacking tunnel departs from Qidu island, then passes underneath north levee road, viewing platform, Ou River and Ou River road, finally reaches the received well. The net distance between tunnel segment and the viewing platform piles is only 230mm. In order to analyze the negative influence of large diameter pipe-jacking tunnel traversing piles of viewing platform, the numerical model is established, and the levee road settlement value is found which matches with observed settlement very well. The dynamic analysis is also conducted by El Centro seismic wave, and the result reveals that the max displacement occurs on the segment between the rear row piles of viewing platform, and the max displacement reaches 68.6mm in the earthquake.

1. Introduction
The soft soil layers such as silt and silty clay distributes in Tianjin, Shanghai, Wenzhou and some other coastal cities extensively, and the soft soil layers are higher water content and less deformation modulus, so the large displacement and deformation occur obviously when the soft soil was disturbed. Underground engineering Construction is difficult in deep soft soil layers, especially in the area where is close to structures, underground utilities. Construction work is easy to bring adverse effect on the adjoining structures, so the engineering analysis is necessary before the project construction, and then take some measures to reduce adverse effect for nearby structures.

2. Project Profile
The power tunnel crosses Ou River in Wenzhou city, and the beginning well sunk in Qidu island while the receiving well sunk in Ou River road treelawn. The total pipe-jacking distance is 1202m. The power tunnel starts from Qidu island, then passes underneath levee crown road, Ou River and Ou River road consecutively, and reaches the receiving well at last. The power tunnel’s external diameter is 4.14m while the distance between adjacent piles is 5.4m. The concrete piles’ diameter is 800mm. The net distance between tunnel and piles is only 0.23m.
3. Project Geological Condition
The geological exploration reveals 5 layers by physical & mechanical characters, lithology & hidden rule. Some geological layers are subdivided into secondary layers and sandwich layers. The soil layers is ①1 miscellaneous fill, ②clay, ③1 silty sand,③1 silt, ③2 sandy silt, ③3 silt, ③4 sandy silt, ④1 silty clay, ⑤1 clayey silt, ⑤11 clay,⑤12 silty clay, ⑤2 pebble respectively from top to bottom. The power tunnel is constructed in silt layer, and the soil’s parameters are listed in table1:

| Serial number | layer          | depth/m | Gravity/kN/m³ | φ° | Es/MPa |
|---------------|---------------|---------|---------------|----|--------|
| 1             | clay          | 1.2     | 16.7          | 19.98 | 12.33 |
| 2             | Sandy silt    | 4.3     | 16.9          | 4.68 | 18.63 |
| 3             | silt          | 21      | 17            | 12.1 | 10     |
| 4             | Silty sand    | 1       | 18.6          | 10   | 18     |
| 5             | Silty clay    | 9.1     | 17.5          | 17   | 13.8   |
| 6             | Clayey silt   | 2.5     | 19.9          | 13.01 | 23.22 |
| 7             | pebble       | 20.9    | 22            | 0    | 32     |

4. Pipe Jacking Passes Through Closely to the Viewing Platform Piles
The viewing platform basement includes double row piles. The diameter of front row piles is 800mm whose axial distance is 5.4m. The pile length reaches 35m, which is constructed by C25 concrete. The length of back row pile is 15m, and other parameters are same to front row pile. The relative position of tunnel and piles is shown in the figure 2.

(a)The longitudinal profile(b)The cross section profile

Figure 2. The relative position of tunnel and pile.
In order to survey the concrete pile’s real position and quality, the piles are need to be measured before the tunnel passes through. The survey method is in figure3.

(a)The planform of piles and sound-pipes   (b)The profile of piles and sound-pipes

Figure 3. The net distance surveying between piles.

The surveying is conducted as follow:
1) Place the piles and sound-pipes exactly, and vertical plan of sound-pipes parallels the vertical plane of electric power tunnel axis.
2) Drilling vertical hole in the site of surveying inclined hole, and the axis is projected on the levee slope, thus control the precision of vertical plan of surveying inclined hole.
3) Drill stem drills into soil slantways at a specific angle, and the aiguille diameter is 20mm. In the middle of exploration hole, the hole diameter expands to 100mm to set oriented pipe.
4) Stop drilling when the drill stem touches pile surface, and records the drilling length, then puts the inclinometer into the hole. In order to guarantees the cross oriented slot parallels the vertical plane, the cross slots posture should be control accurately.
5) Each measuring point was measured by inclinometer along two orthogonal planes of the cross guide groove of the surveying pipe. Within the height range of the tunnel pipe, at least three measuring points were given for each pile to give a more accurate net distance between piles. The detection results show that the theoretical value of net distance between piles in the front row adjacent river is 4600mm, and the measured value is 4564mm. The theoretical value of net distance between rear piles is 4730mm, and the measured result is 4693mm. Both front and rear piles have small protruding, but it can meet the requirements of pipe jacking passing through the piles.

5. Adverse Effect of Pipe Jacking on the Embankment Top Road
In order to analyze the adverse effects of pipe jacking on the top road of Ou River embankment, settlement observation points are uniformly arranged in the direction perpendicular to the axis of the power tunnel on the top road of the embankment. The six monitoring points close to the tunnel is located as shown in figure 4:
Figure 4. The service point of levee road displacement.

The corresponding relationship between the observation point settlement and the horizontal distance to the tunnel central axis is shown in Figure 5. The monitoring points’ settlement law is obtained, as shown in Formula (1):

\[
s = 2 \times 10^{-6} \cdot D^4 + 5 \times 10^{-5} \cdot D^3 + 5 \times 10^{-4} \cdot D^2 + 2.1 \times 10^{-3} \cdot D - 3.6485 \quad (1)
\]

where:
\( R^2 = 0.961 \)

\( s \) — settlement, mm;

\( D \) — horizontal distance to the tunnel central axis, mm.

Figure 5. The settlement of observation points.

6. Numerical Simulation of the Impact of Pipe-Jacking on the Environment Near Viewing Platform Pile Foundation

According to the soil layers revealed in the geological exploration report, a calculation unit with a width of 6m is selected. The numerical model is shown in figure 6:

Figure 6. The model of viewing platform and tunnel under the levee.
The design elevation of the water level of Ou River is 0.8m, and the elevation of the XK-13 hole near the viewing platform is -6.12m. Considering that the water level reaches the design level in the process of pipe jacking construction, 7m water pressure is loaded on the bottom of the river. As the pushing force of the pipe jacking cutter head is balanced with the active earth pressure on the face of the tunnel, the pushing force is acted on the face of the tunnel during the pipe jacking process in the numerical model. When the pipe-jacking passes through the embankment and the pile foundation of viewing platform, the maximum calculated settlement of the embankment is 2.0mm, and the actual observed average value of the observation points is 3.2mm. The difference between the calculated value and the measured value is 1.2mm. This difference may be caused by the change of the swelling mud pressure around the segment after the pipe-jacking cutter head cutting the soil. When the pipe is pushed through, the settlements of embankment top road and the piles are shown in figure 7.

![Figure 7. The soil and piles displacement when machine jacking through the levee road.](image)

After the pipe jacking through the embankment and viewing platform, the distribution of von-Mises stress on the segment structure is shown in figure 8:

![Figure 8. The Von-Mises distribution on segments.](image)

7. Study on Seismic Dynamic Response of Tunnel Structure and Soil
The 1940 El Centro Site seismic wave was adopted in numerical model. The peak acceleration is 0.3569g and the duration of the seismic wave is 53.72 seconds. The acceleration curve of the seismic wave is shown in figure 9.
Figure 9. The curve of earthquake acceleration.

The top six vibration modes of piles and tunnel are shown in figure 10:

(a) $F=0.2635\text{Hz}$  (b) $F=0.3016\text{Hz}$  (c) $F=0.3032\text{Hz}$  (d) $F=0.7327\text{Hz}$

(e) $F=1.3359\text{Hz}$  (f) $F=1.3437\text{Hz}$

Figure 10. The first six modes of piles and tunnel.

Figure 11. The max displacement of tunnel and piles in the earthquake.

As can be seen from figure 11, under the action of EI Centro seismic wave, the maximum displacement of the tunnel structure is 68.6mm. The maximum displacement pipe is between the rear row piles underneath the viewing platform. With the increase of the distance to the pile foundation, the maximum displacement of the pipe segments decreases gradually.

8. Conclusion

The Ou River power tunnel has an outer diameter of 4.14m and passes between two 35m piles on the north landscape platform. The net distance between the surface of the segment and the piles is only 230mm. By the accurate detection of pile foundation and the precisely control of pipe-jacking during construction, the pipe-jacking tunnel traversed the pile foundation successfully, and the settlement of
embankment top road was controlled in the limitation, and the average settlement of measuring points is only 3.2mm.

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