Deformation characteristics and internal force analysis of shield hoisting construction of working shaft in silty clay strata: Case study in Jinan

Yao Lu¹, Hongjun Liu¹-², Jian Chen¹-³, Xiuting Su¹, and Tao Liu¹-²,*
¹College of Environmental Science and Engineering, Ocean University of China, Qingdao, Shandong, 266100, China
²Key Laboratory of Shandong Province for Marine Environment and Geological Engineering, Ocean University of China, Qingdao, Shandong, 266100, China
³China Railway 14th Bureau Group Co., Ltd., Jinan, Shandong, 250000, China

*Corresponding author: ltmilan@ouc.edu.cn

Abstract. Unlike a conventional shield machine, a large-diameter shield machine needs to be hoisted separately with large hoisting equipment because of its heavy weight and large volume. Therefore, hoisting process control is important for the safety of the working shaft. By examining the shield hoisting of the Jinan Yellow River Tunnel project, this paper studied the influence of large-diameter shield hoisting on the working shaft in silty clay strata under the worst working conditions (358 t shield cutterhead load + 650 t and 300 t crawler crane loads). A three-dimensional numerical model was conducted to investigate the ground settlement, horizontal and vertical displacements of the retaining wall, and internal force in the process of shield hoisting. Field monitoring data were adopted to validate the results of the numerical analysis. The results showed that the following. (1) During the shield hoisting process, the ground settlement in the hoisting area was obviously larger than that outside it, whose maximum settlement reached 7.35 mm. (2) The horizontal displacement in the center of the retaining wall was the greatest, which reached 3.4 mm. When the depth of the foundation pit was 22 m, the maximum displacement was 9.2 mm. (3) The maximum bending moment was 1625.5 kN·m, located at the foundation pit depth of 22 m, which was about two-thirds of the total pit depth. (4) The monitoring data showed that the maximum ground settlement during the shield hoisting was approximately 8.4 mm. The value was 12.5% different from the simulated maximum settlement of 7.35 mm. The maximum horizontal displacement value of the retaining wall was 5.2 mm.

1. Introduction
Underground space is becoming increasingly important for relieving traffic congestion [1]. Shield tunneling is typically conducted to excavate underground tunnels [2,3]. The shield tunnel construction process is mainly divided into launching, tunneling, and receiving. The shield hoisting operation is an important premise for the success of the shield engineering. Shield machines, especially large-diameter ones, are heavy; thus, they are often transported to the working shaft by means of separate hoisting. The assembly operation is then conducted at the bottom of the shaft. In this process, the
working shaft bears a great load of the hoisting construction, which has an adverse impact on the safety of the deep foundation pit. The internal force of the support structure changes rapidly at the moment of shield hoisting. Therefore, the stability of shield hoisting construction should be studied to ensure reasonable and safe construction.

Research on deep foundation pits mainly focuses on the impact of foundation pit excavation on the surrounding environment [4-7]. Only a few groups have studied the deformation and internal force of deep foundation pits with the pit side bearing the maximum load. Huang Zhuwei [8] simulated the internal force distribution and deformation law of a foundation pit under five different combinations of surcharge. They obtained different degrees of influence on the structure and its surrounding under an asymmetric surcharge of the pit side. Wang Peixin, Zhou Shunhua et al. [9] studied the stress of a retaining structure that was unsymmetrically loaded in a foundation pit adjacent to a railway. They suggested that the integral characteristics of such an unsymmetrically loaded structure and the interaction between the two foundation pits should be considered in the design phase. Guo Panpan, Gong Xiaonian et al. [10] described the displacement and force behavior of a braced deep excavation under the unsymmetrical surcharge effect. The FD method was validated by a close match between wall displacements and bending moments, and the results of the beam-on-elastic-foundation method and field monitoring data. M N Houhou et al. [11] conducted a three-dimensional finite difference analysis of a deep excavation braced by diaphragm walls. The results indicated that the maximum horizontal wall displacements were almost threefold the maximum ground settlements. Yao Aijun and Zhang Xindong [12] used field measurement to analyze the displacement of a pile and the axial force of steel support on both sides of a deep foundation pit under asymmetric load.

In general, prior work is limited to a subset of the impact of foundation pit construction on the surrounding environment. Further research is needed to understand the safety of large-diameter shield machine hoisting in silty clay strata. The surcharge effect on a deep excavation has an unsymmetrical distribution relative to the excavation geometry, thereby posing danger to the project. In this paper, a three-dimensional numerical model was conducted to investigate the hoisting safety of a working shaft in silty clay strata under the most unfavorable working conditions (358 t shield cutterhead load + 650 t and 300 t crawler crane loads). Then, field monitoring data were adopted to validate the numerical analysis results.

2. Analytical model of retaining structure

In the current theoretical calculations, the retaining structure was usually analyzed as an elastic foundation beam to solve the displacement occurring after pit excavation. The beam-on-elastic-foundation method, sometimes termed Winkler’s model, is the most widely used method of analyzing soil–structure interaction problems [13]. A schematic diagram of the beam-on-elastic-foundation method for the analysis of retaining walls is shown in figure 1.
The plane elastic foundation method assumes that the retaining structure is a plane strain problem, and the retaining wall of unit width is taken as the vertical elastic foundation beam. The supports and bolts are simplified as strut springs. The soil below the excavation bottom in the foundation pit is simulated by soil springs. Outside the retaining structure is Rankine active earth pressure. The deformation differential equation of the beam-on-elastic-foundation method is as follows:

\[ EI \frac{d^4 y}{dz^4} - e_a(z) = 0 \quad (0 \leq z \leq h_n), \quad (1) \]

\[ EI \frac{d^4 y}{dz^4} + mb_h(z - h_n)y - e_a(z) = 0 \quad (z \geq h_n), \quad (2) \]

where \( EI \) is the bending stiffness of the retaining wall, \( y \) is the lateral wall deformation, \( z \) is the depth below the ground surface, \( e_a(z) \) is the Rankine active earth pressure at depth \( z \), \( m \) is the scale factor for the horizontal coefficient of subgrade reaction, and \( h_n \) is the excavation depth at the \( n \)th stage.

Considering the stratification of soil (different \( m \) values) and the existence of horizontal support, the beam on the elastic foundation is vertically divided into several elements. The above differential equation of each element should be established. Generally, the finite element method of bar system can be used to solve the problem. In the analysis of layered excavation with multiple supports, construction conditions are divided according to foundation pit excavation and support. The deformation and internal force of the retaining structure are calculated according to the sequence of conditions. Variations in boundary conditions and load forms under different working conditions should be considered. Finally, the envelope displacement calculated under the previous working condition is regarded as the initial value of the next working condition.

3. Engineering background

3.1. Project overview

The Jinan Yellow River Tunnel is at the central axis of the city and connects Queshan in the north and Jiluo road in the south. It has a total length of 4.76 km, including the 3.89 km Yellow River Tunnel, a 0.87 km connecting road, and related ancillary works. The vertical distances from Jianbang Yellow River Bridge and Jinan Yellow River Bridge to the tunnel are 5.3 km and 5.1 km, respectively (figure 2). A large-diameter slurry shield machine (D=15.76 m) was used in this project. The tunnel adopts the co-construction scheme of the urban road and the M2 line, which is a super-large-diameter shield tunnel.
The foundation pit of the working shaft in the north bank starts at the right EK3+520.510 and ends at the right EK3+672.710. After operation, the foundation pit of the working shaft is used for equipment storage. The width of the working shaft is 34.14–50.0 m, and the length is 152.2 m. The thickness of the covering soil of the structure is about 3.0 m, and the buried depth of the floor is about 26.2–31.0 m.

**Figure 2.** Tunnel alignment of the Jinan Yellow River Tunnel: (a) location of the project; (b) details of the project.

### 3.2. Site conditions

The working shaft in the north bank is located in the alluvial plain, and the local micro-geomorphic unit is the Yellow River bed. According to a ground investigation, the soil profile on both banks mainly consists of silty clay (figure 3).

**Figure 3.** Geological profile.

### 3.3. Foundation pit engineering retaining structure on north bank

The retaining structure of the foundation pit on the north bank is composed of an underground retaining wall and bored piles. The maximum excavation depth of the foundation pit is about 31.2 m, the thickness of the underground retaining wall is 1.2 m, and the depth is 47.0–51.5 m. Five to seven concrete and steel supports are provided in the depth range of the foundation pit. The horizontal spacings of the reinforced concrete support and steel support are 7 m and 3.5 m, respectively. The continuous beam of the reinforced concrete support is 800×1000, and the continuous
beam steel support is an HN400×200. The temporary column adopts a 4L200×200×20 steel lattice column (Q235b steel). The foundation pit is constructed in a sequential manner, and the underground retaining wall and bored piles are made of C30 reinforced concrete. The layouts of the support plans are shown in figure 4.

![Support plan](image1)

(a) (b)

**Figure 4.** Support plan: (a) concrete support plan; (b) steel support plan.

### 3.4. Hoisting site layout and hoisting plan

#### 3.4.1. Hoisting site layout.

The assembly site should be optimized according to the construction needs, and the placement of each part of the shield machine should be reasonably arranged. After the shield machine arrives at the site, it should be unloaded to the designated location with a crawler crane and a truck crane according to the site layout. The layout of shield hoisting is shown in figures 5 and 6. 1#: 20.85×22 m, 2#: 14×13.5 m, 3#: 18×13.5 m.

#### 3.4.2. Hoisting plan.

The shield’s main engine is lowered into the shaft from the #1 hoisting port, and a shield installation base is placed at the bottom of the shaft. The main components of the shield are the front shield, tail shield, main drive (largest component, weighing 370 t), and assembly. These components are mainly lifted by a 650 t crawler. The shield machine’s cutterhead, which weighs 358 t, is lowered into the shaft from the #1 hoisting port, and the overall hoisting method is adopted. Then, 650 t and 300 t crawler cranes are used for hoisting and lowering, respectively. The southeast end of the hoisting port is used as the assembly and stacking site of the cutterhead ground. The southwest end is used as the hoisting site of the crawler crane. Thus, the 358 t shield cutterhead load and 650 t and 300 t crawler crane loads constitute the worst working conditions in the hoisting process.

![Layout of shield hoisting](image2)

**Figure 5.** Layout of shield hoisting.

![Field diagram in red dashed-line box](image3)

**Figure 6.** Field diagram in red dashed-line box in figure 5.
4. Three-dimensional numerical analysis

4.1. Geotechnical properties

A constitutive model and its parameters significantly affect the accuracy of its results [14]. A linear elastic model was adopted for the concrete materials, and the Mohr–Coulomb model was adopted for each layer of soil. The soil layer and the foundation were simulated by solid elements, and the existing subway structures were simulated by beam elements. The soil parameters in the model were selected with reference to geological prospecting data. The geotechnical properties are shown in Table 1.

| Soil                  | \( \gamma \) (kN/m\(^3\)) | \( \phi \) (\(^\circ\)) | \( c \) (kPa) | \( V \) | E(MPa) |
|-----------------------|-----------------------------|--------------------------|--------------|------|--------|
| Sandy silt            | 19.5                        | 15.6                     | 20.0         | 0.33 | 10.0   |
| Silty clay            | 19.1                        | 14.6                     | 17.0         | 0.33 | 12.0   |
| Silty fine sand       | 20.4                        | 17.1                     | 37.3         | 0.28 | 16.0   |
| Calcareous tuberculosis | 21.0                    | 20.0                     | 30.0         | 0.30 | 50.0   |
| Fully weathered gabbro | 22.0                    | 38.0                     | /            | 0.35 | 800.0  |
| Concrete              | 25.0                        | /                        | /            | 0.20 | 3.35e4 |

4.2. Modeling

There were two risk points in this project. The first one was the safety of the construction process of the main structure of the north bank working shaft on the existing structure. The second risk point was the safety impact of the shield machine load hoisting in the reinforcement area on the main structure of the working shaft (358 t shield cutterhead load + 650 t and 300 t crawler crane loads).

On the basis of these risk points, a three-dimensional numerical model of the work shaft foundation pit in the north bank of the Yellow River Tunnel project in Jinan was established. The calculation scope of this model was determined according to the construction condition of the main structure of the north bank working shaft. The range was 350×180×100 m, and the calculation model had 123,541 nodes, as shown in figure 7.

The plate element model was adopted for the wall and the floor. The beam element model was used for the enclosing purlin, pull-out pile, and vertical column. A three-dimensional solid element was used to calculate the soil of each layer and the reinforcement area of the rotary jet pile on one side of the shaft.

4.2.1. Meshing.

Given the complexity of the geometry, the smaller the mesh size, the higher the mesh quality, but the longer the corresponding modeling time. Therefore, the efficiency and quality of the mesh should be considered to determine the mesh size. In this model, the spacing around the working shaft on the north bank of the Yellow River Tunnel in Jinan was 3 m, and the spacing between the edges of the site was 5 m. For the connection of the geotechnical elements and nodes, it was not necessary to generate solid structural elements. Instead, structural elements should be extracted through the surface or line of the generated grid. The disjunction function could obtain the node location according to the generated geotechnical element. In this model, the subterranean retaining wall and pipe wall were created by a disjunctive function. The 1D grid was divided to generate an implantable beam (concrete support and steel support) that did not need a nodal connection with the adjacent geotechnical units, and the structural elements (extruding piles, columns, and enclosing purlins) were created through the disjunction function.
4.2.2. Boundary conditions.
The boundary conditions were set by operating the setting constraints of the translational and rotational degrees of freedom in the model based on the global coordinate system. They were defined as follows. The ground surface was free to displace. In the vertical boundaries, only the normal directions were fixed, and the base was also fixed [15].

4.2.3. Load calculation.
Three aspects were considered in the calculation of the working conditions: (a) the vertical dead weight of soil, (b) local ground overload of 25 kPa, and (c) hoisting load of the shield tunneling machine. According to the actual hoisting construction situation, there was a 358 t shield cutterhead load and 650 t and 300 t crawler crane loads.

4.3. Results analysis

4.3.1. Ground settlement.
Figure 8 shows the observed ground settlement of the three-dimensional numerical model at 1-1 and 2-2. It is consistent with the shape of a Gaussian curve. The ground settlement in the hoisting area is noticeably larger than that outside the hoisting area, whose maximum settlement reaches 7.35 mm. Although the hoisting area is reinforced, it still causes a large settlement because of the heavy hoisting.

4.3.2. Displacement of retaining wall.
Because of the space effect, the horizontal displacement in the center of the retaining wall, which reaches 3.4 mm, is the greatest (figure 9). The horizontal displacement decreases from the center to both sides. The minimum deformation, which is close to zero, occurs at the working shaft corner. As shown in figure 10, with the increase in depth, the horizontal displacement of the working well increases gradually. When the depth of the foundation pit is 22 m, the maximum displacement is 9.2 mm. After the maximum displacement is reached, the horizontal displacement gradually decreases. When the retaining wall reaches a depth of about 45 m, its horizontal deformation becomes almost zero because it reaches the rock; that is, the deformation becomes smaller.
4.3.3. Internal force of retaining wall.
The bending moment of the retaining wall on the hoisting side is greater than that on the non-overloading side. During hoisting, the maximum bending moment is 1625.5 kN·m, which is located at a depth of 22 m in the foundation pit, which is about two-thirds of the total pit depth (figure 11).

![Diagram](image1)

**Figure 8.** Ground settlement. **Figure 9.** Horizontal displacement of retaining wall.

![Diagram](image2)

**Figure 10.** Horizontal displacement in the depth direction. **Figure 11.** Bending moment.

5. Field measurement

5.1. Monitoring program
The influence of external loads on the structure of the working shaft during the shield hoisting was monitored according to the foundation pit excavation and main structure construction of the working shaft on the north bank of the Yellow River Tunnel project in Jinan. The deformation characteristics of the structure of the working shaft were analyzed.

There were 25 groups of ground settlement monitoring points, 125 in total, and 25 horizontal and vertical displacement of the top of the retaining wall in the Yellow River Tunnel. In this paper, the monitoring points (figure 12) at the #1 hoisting port were selected to analyze the deformation characteristics of the working shaft during hoisting. The monitoring and control indicators are shown in table 2.

| Table 2. Monitoring and control indicators. |
### 5.2. Monitoring data analysis

As seen in figure 13, the ground settlement fluctuates when other parts of the shield are constructed. When the heavy cutterhead is hoisted, the maximum settlement is 8.4 mm. The value is 12.5% different from the simulated maximum settlement of 7.35 mm. The settlement of the monitoring point near the working shaft is greater. The further away from the edge of the foundation pit, the less the ground subsidence.

In the hoisting of the cutterhead, the horizontal deformation of the underground retaining wall increases rapidly (figure 14). The maximum value is 4.1 mm, and it occurs on the hoisting side. This value deviates from that of the numerical simulation by 17.1%. However, the variation in the side that does not directly bear the hoisting load is relatively small, but the trend is consistent. They all tend to deform to the inside of the foundation pit. The change in the vertical load of the underground retaining wall...
wall is not evident when the cutterhead is hoisted. Its variation law is similar to that of the horizontal displacement (figure 15).

Figure 16 indicates that the basic trend of the simulation results is consistent with the monitoring data. Both of them reach the maximum value of the horizontal displacement at the depth of 20–25 m. However, the monitoring displacement change is larger than the simulation result, and the maximum displacement is 13.4 mm. This is because the actual construction is more complicated than simulated conditions.

![Figure 13. Ground settlement. Figure 14. Horizontal displacement.](image1)

![Figure 15. Vertical displacement. Figure 16. Comparison of simulation and monitoring data.](image2)

6. Conclusions
Based on the Jinan Yellow River Tunnel project, this paper studied the worst conditions of shield hoisting. The main conclusions are as follows.

(1) During the shield hoisting process, the ground settlement of the three-dimensional numerical model was basically consistent with the shape of a Gaussian curve. The ground settlement in the hoisting area was evidently larger than that outside the hoisting area, whose maximum settlement reached 7.35 mm.

(2) The horizontal displacement in the center of the retaining wall was the greatest, which reached 3.4 mm. With the increase in depth, the horizontal displacement of the working well increased gradually. When the depth of the foundation pit was 22 m, which was about two-thirds of the foundation pit depth, the maximum displacement was 9.2 mm.
During hoisting, the maximum bending moment was 1625.5 kN·m. This occurred at a depth of 22 m in the foundation pit, which was about two-thirds of the total pit depth.

According to the monitoring data, the maximum ground settlement during shield hoisting was about 8.4 mm. The value was 12.5% different from the simulated maximum settlement of 7.35 mm. The maximum horizontal displacement value of the retaining wall was 5.2 mm, which occurred on the hoisting side.

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