Analysis of Influence on the Super-Large-Diameter Shield Tunnel by Stockpile Unloading

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Abstract. As the super-large-diameter shield tunnel sprouts up, there will be more and more constructions adjacent to the super-large-diameter shield tunnel. As the newly-built structure changes the existing stress field, it will inevitably deform the super-large-diameter shield tunnel and bring hazard. Based on the soil stockpile adjacent to Ying Bin San Lu shield tunnel in the flight area of Shanghai Hongqiao Airport, the digital model was established by PLAXIS finite element analysis software to analyze the influence on the super-large-diameter shield tunnel by the soft soil area and different stockpile unloading time sequence. According to the findings, it’s recommended to carry out massive stockpile unloading adjacent to the shield tunnel in section and in layer and conduct unloading first when far from the tunnel, thereby minimizing influence on the shield tunnel.

1. Introduction
As China’s urbanization speeds up, the ground space available becomes narrower while more effort is put on underground space development. Therefore, the super-large-diameter shield tunnel is widely used in highway construction. According to statistics, as of June 2016, there were 36 shield tunnel projects with a diameter of 14 m and above, including 15 overseas projects and 21 domestic projects [1-7]. As the super-large-diameter shield tunnel sprouts up, there will be more and more constructions adjacent to the super-large-diameter shield tunnel. As the newly-built structure changes the existing stress field, it will inevitably deform the super-large-diameter shield tunnel and bring hazard. Based on the soil stockpile adjacent to Ying Bin San Lu shield tunnel in the flight area of Shanghai Hongqiao Airport, the digital model was established by PLAXIS finite element analysis software to analyze the influence on the super-large-diameter shield tunnel by the soft soil area and stockpile unloading.

2. Project profile
Located in the south side of Hongqiao Airport, Shanghai Ying Bin San Lu shield tunnel begins from SN6 Road in the west, runs from Ying Bin San Lu downward toward Qixin Road, North Hengli Port, South Side of Hongqiao Airport, Railway 101, comes above ground along the existing Ying Bin San Lu and stops at A20 Road. The project has a total length of about 3,166 m, with the length of shield tunnel around 1,861m. [8]

Ying Bin San Lu shield tunnel is composed of lower lane and upper lane, as shown in Figure 1. The lower lane has a “π” prefab in the middle, with both sides compacted by the plain concrete. The
upper lane is composed of cast-in-situ lane plate, frame beam, column and pedestal. The column and pedestal are connected by the planted bar and segment.

The flight area of Shanghai Hongqiao Airport has 6 stockpiles formed in 2008–2009. The stockpile to be unloaded is located in the Ying Bin San Lu tunnel crossing the south side of the flight area (South Stockpile). The outer sideline of Ying Bin San Lu tunnel has the shortest distance of about 21.28 m from the slope foot of south stockpile and ~32.82 m from the slope top of south stockpile, as shown in Figure 2. According to field survey, the length of four sides of the slope foot of south stockpile: ~127.58 m, ~207.18 m, ~132.30 m, ~205.33 m; the length of four sides of the slope top of south stockpile: ~108.38 m, ~187.32 m, ~111.75 m, ~188.26 m; slope foot elevation: 2.64 ~ 3.26 m; slope top elevation: 5.44 ~ 8.69 m; stockpile height ~5-7 m. The stockpile is mainly composed of building waste mixed with cohesive soil, characterized by complex composition and poor uniformity.

The field geological conditions are composed of 9 soil layers, from top to bottom, soil mound, ① filling soil, ② powder clay, ③ powder clay with powder sand, ④ silt clay, ④T gray sandy silt, ⑤ powder clay, ⑥ powder clay with silt, ⑥T sandy silt with powder clay.
powder clay, ⑤③ powder clay with silt, ⑤① sandy silt with powder clay. The main working soil layers of Ying Bin San Lu tunnel, from top to bottom, ④①, ⑤①, ⑤③①, as shown in Figure 3.

3. Calculation Model

3.1. Calculation model

![Figure 4. Digital model](image1)

![Figure 5. Unloading area](image2)

PLAXIS finite element analysis software was used to simulate the influence on the Ying Bin San Lu shield tunnel by the south stockpile unloading. According to the south stockpile scope, height and burial depth of Ying Bin San Lu tunnel, the digital model size was determined to be 358×61m, as shown in Figure 4. There are 9 soil layers. Hardening-Soil model was used for 2D simulation. The shield segment and internal structure were simulated by the linear unit. The soil layers and structural parameters are given in Table 1 and 2.

| Name of soil layer                                | Unit weight $\Gamma$(kN/m$^3$) | Cohesion C(kPa) | Internal friction angle $\phi$(°) | Cutting modulus $E_{50-ref}$(kPa) | Tangential modulus $E_{0ed-ref}$(kPa) | Reloading modulus $E_{ur-ref}$(kPa) |
|--------------------------------------------------|--------------------------------|-----------------|----------------------------------|-----------------------------------|-------------------------------------|-----------------------------------|
| Soil mound                                       | 19                             | 21              | 15.2                             | 10000                             | 6000                                | 50000                             |
| ①① Filling soil                                 | 18.9                           | 21              | 15.2                             | 9000                              | 9000                                | 54000                             |
| ②① Powder clay                                  | 18.9                           | 21              | 15.2                             | 9000                              | 6430                                | 54000                             |
| ③ Powder clay with powder sand                  | 17.6                           | 12              | 15.3                             | 7500                              | 7500                                | 60570                             |
| ④ Silt clay                                     | 17.0                           | 11              | 11.7                             | 6500                              | 5000                                | 34130                             |
| ④① Sandy silt                                   | 18.2                           | 2               | 31.1                             | 18850                             | 18000                               | 56550                             |
| ⑤① Powder clay                                  | 17.7                           | 13              | 12.0                             | 10690                             | 10000                               | 53450                             |
| ⑤③① Powder clay with silt                      | 17.9                           | 15              | 18.9                             | 11590                             | 7000                                | 46360                             |
| ⑤①③ Sandy silt with powder clay                | 18.1                           | 3               | 29.7                             | 26130                             | 15700                               | 78470                             |

As the segment masonry is an entirety where segments are bolted. As it’s microscopically anisotropic, multiply rigid reduction coefficient 0.8 in case of masonry by homogeneous equivalent segment.
3.2. Calculation work conditions

The south stockpile is divided into four areas A, B, C and D from far to near. According to unloading height, each area is composed of 2 layers and each layer thickness is controlled at 2–3 m, as shown in Figure 5.

### Table 2. Structural unit specification

| Item            | Structural type | Elastic modulus $E$ (kN/m²) | Poisson’s ratio $\mu$ | Weight density $\rho$ (kN/m³) | Section width $B$ (m) | Section height $H$ (m) |
|-----------------|-----------------|-----------------------------|-----------------------|-------------------------------|----------------------|-----------------------|
| Round tunnel    | 1D unit         | $3.15 \times 10^7$         | 0.15                  | 25                            | 1                    | 0.6                   |
| Lane plate      | 1D unit         | $3.15 \times 10^7$         | 0.15                  | 25                            | 1                    | 0.52                  |
| Column          | 1D unit         | $3.15 \times 10^7$         | 0.15                  | 25                            | 0.5                  | 0.5                   |
| Lower lane      | 1D unit         | $3.15 \times 10^7$         | 0.15                  | 25                            | 1                    | 0.35                  |

4 calculation work conditions are considered in terms of influence analysis. The influence on Ying Bin San Lu tunnel by south stockpile unloading is shown in Figure 3 according to different unloading sequences (layer excavation and segment excavation).

### Table 3. Calculation work condition

| Work condition     | Unloading sequence | Remarks                                                                 |
|--------------------|--------------------|-------------------------------------------------------------------------|
| Work condition A   | D1→D2→C1→C2        | • Excavate from far to near;                                            |
|                    | B1→B2→A1→A2        | • Soil mound excavation till ground before excavating the next segment of soil mound |
| Work condition B   | D1→C1→B1→A1        | • Excavate from far to near;                                            |
|                    | D2→C2→B2→A2        | • Excavate the topsoil before excavating the next soil layer;          |
| Work condition C   | A1→A2→B1→B2        | • Excavate from near to far;                                            |
|                    | C1→C2→D1→D2        | • Soil mound excavation till ground before excavating the next segment of soil mound |
| Work condition D   | A1→B1→C1→D1        | • Excavate from near to far;                                            |
|                    | A2→B2→C2→D2        | • Excavate the topsoil before excavating the next soil layer;          |

### 4. Calculation Results and Analysis

#### 4.1. Calculation results

### Table 4. Summary of calculation results

| Work condition | Type            | Total displacement (mm) | Horizontal displacement (mm) | Vertical displacement (mm) |
|----------------|-----------------|-------------------------|------------------------------|---------------------------|
| Work condition A | Land deformation | 28.40                   | 28.36                        | -19.14                    |
| Work condition B | Land deformation | 11.34                   | 11.22                        | -2.34                     |
| Work condition B | Tunnel deformation | 30.11                  | 30.08                        | -20.18                    |
| Work condition C | Land deformation | 13.71                   | 13.60                        | -2.74                     |
| Work condition C | Tunnel deformation | 31.15                 | 31.13                        | -18.06                    |
| Work condition D | Land deformation | 14.25                   | 14.14                        | -2.79                     |
| Work condition D | Tunnel deformation | 33.33                 | 33.32                        | -19.00                    |
Due to words limit, only all results of work condition A are displayed. Under other work conditions, the summary of structural deformation results is presented in Table 4.

Work condition A. After south stockpile unloading, the largest land deformation is 28.40 mm, located adjacent to the slope foot of south stockpile far from Ying Bin San Lu tunnel. The unloading soil has the loading effect, which may reduce the unloading effect on the layer stress, as shown in Figure 6 (a). After the south stockpile unloading under work condition A, the land’s maximum horizontal deformation and vertical deformation are both located near the slope foot of south stockpile far from Ying Bin San Lu tunnel. Their values are respectively 28.36 mm and 19.14 mm, as shown by (b) and (c) in Figure 6. Ying Bin San Lu shield tunnel has the horizontal deformation of 11.22 mm, moving toward the south stockpile. It has the vertical deformation of 2.34 mm, moving downward. Generally speaking, the existing tunnel structural deformation mainly moves towards the south stockpile, as shown in Figure 7 and Figure 8.

4.2. Result analysis
Summary of calculation results under four work conditions is given in Table 4.

According to Table 4, the land deformation and tunnel structure deformation under work condition A are minimum. Therefore, the work condition A represents the optimal plan. The work condition D has the biggest deformation, with total tunnel displacement 15.03 mm > 15.00 mm.

Under work condition A, the final horizontal displacement of Ying Bin San Lu tunnel is 11.22 mm and the final vertical displacement is -2.34 mm. Because the cumulative up float of Ying Bin San Lu shield tunnel is ~9 mm, under work condition A, the expected final horizontal displacement overlap of Ying Bin San Lu shield tunnel is 11.22 mm and the expected final vertical displacement overlap is 2.34+9=11.34 mm. The tunnel structure also abides by the control criteria of settlement and horizontal
displacement $\leq 15$ mm. We draw the conclusion that unloading south stockpile as per work condition A can ensure the structural safety of the existing Ying Bin San Lu shield tunnel.

![Figure 7. Horizontal deformation details of round tunnel (work condition A) (unit: mm)](image)

![Figure 8. Vertical deformation details of round tunnel (work condition A) (unit: mm)](image)

5. **Actually measured settlement data**

The actually measured settlement data of Ying Bin San Lu shield tunnel of south stockpile unloading are given in Figure 9. Since the south stockpile unloading commencement, Ying Bin San Lu shield tunnel settles before rises. During early unloading, the overload arising out of equipment mobilization causes existing shield tunnel settlement around $-0.3$ $\sim$ $2.0$ mm. As the unloading continues, the existing shield tunnel begins to rise up to $5.3$ mm. The final rise gets stabilized at $2.3$ $\sim$ $3.8$ mm, relatively consistent with the expected results herein.

![Figure 9. Settlement data](image)

6. **Conclusions**

The finite element digital simulation analysis method was used herein to analyze the influence on the adjacent super-large-diameter shield tunnel by the soft soil area and stockpile unloading. Conclusions:

1. Unload from far to near. The unloading soil has the loading effect, which may effectively control the tunnel deformation. It means that work condition A represents the optimal plan.

2. Under work condition A, the maximum horizontal displacement and maximum vertical displacement of Ying Bin San Lu shield tunnel arising out of south stockpile unloading are respectively $11.22$ mm and $-2.34$ mm. The existing tunnel rise is $9$ mm, and additional settlement $11.34$ mm, complying with the control criteria of the additional settlement and horizontal displacement $\leq 15$ mm.

3. It’s recommended to carry out massive stockpile unloading adjacent to the shield tunnel in section and in layer and conduct unloading first when far from the tunnel.
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