Study on influence partition of tunneling adjacent to multi-storey building in upper-soft and lower-hard stratum

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Abstract: Based on several examples relating to tunneling near the multi-storey building in Qingdao Jiaozhou bay tunnel connecting engineering, the study on influence partition of tunneling adjacent to multi-storey building has been conducted by the finite element strength reduction method. The safety factor of 2.0 was defined as the boundary of the strong to weak influence zone, and the peak safety factor was considered as the boundary of weak to none influence zone. Based on the distribution of safety factors in three cases with relative scale of 2, 1, 1/2, and considering the convenience use on site, a influence partition map of tunneling to the existing multi-storey building in upper-soft and lower-hard stratum has been proposed.

1. Introduction

Since urban rail transit is generally located in the prosperous urban areas with many surrounding buildings and complicated situations, it is often encountered that the tunnels pass directly under the existing buildings at close range. At present, many researches on the influence of tunneling near the buildings have already been conducted [1-6]. Zhao [7] used the Mohr-Coulomb yield criterion to divide the influence zones into the non-influence zone, the weak influence zone and the strong influence zone for overlapping tunneling. These research results have been applied to the design and construction of the overlapping tunnel encountered in Shenzhen metro. Wang [8] used the finite difference method and least squares principle to establish the influence partition of tunneling near the piles, according to different threshold of displacement. Most of the previous studies of the influence partition were based on the indexes of stress, strain and displacement.

This paper involved the index of the safety factor, which was obtained by the strength reduction method, to analyze the influence of tunneling adjacent to the existing multi-storey buildings in upper-soft and lower-hard stratum. This study is based on several cases of tunneling near the buildings in Qingdao Jiaozhou bay tunnel connecting engineering. By calculating the safety factors with various position of tunnel, the influence extent has been quantified, and the influence partition has been proposed.

2. Strength Reduction Method

In 1975, Zienkiewicz proposed the finite element strength reduction method to analyze the safety factor and ultimate load of the engineering [9]. The principle of strength reduction method is listed as:

\[ c' = \frac{c}{\omega} \]  
\[ \phi' = \arctan \left( \frac{\tan \phi}{\omega} \right) \]  

(1)  
(2)
Where $c$ and $\varphi$ are cohesion and internal friction angle respectively before reduction; $c'$ and $\varphi'$ are cohesion and internal friction angle respectively after reduction; $\omega$ is the reduction factor.

When the numerical model reaches the limit state, the reduction factor $\omega$ at this time is the safety factor $F_s$. The limit state is defined by the displacements increasing rapidly of some key points.

### 3. Numerical Calculation

#### 3.1. Numerical model and calculation cases

In Qingdao jiaozhou bay tunnel connecting engineering, there are several cases of tunneling adjacent to the multi-storey buildings with 3~7 storeys. Seven-storey building were taken as the calculation load in this paper, which was estimated to be 0.1MPa.

The numerical model was established in Flac$^{3D}$. The tunnel is considered as ellipse, with 12 meters in height and 16 meters in width. The ground is conformed to the Mohr-Coulomb yield criteria. From top to bottom, as shown in Figure 1, the ground is divided to three layers: intensely weathered granite with 4 meters in thickness, weakly weathered granite with 4 meters in thickness and slightly weathered granite remained.

![Figure 1. Ground and equivalent load of building](image)

![Figure 2. Calculation cases](image)

The calculation cases with different relative locations between tunnel and building are presented in Figure 2. Multi-storey building loading surface was fixed. Due to the symmetry of the calculation model, four angles of 0°, 30°, 60°, and 90° were arranged, and several points were placed at each angle. The relative scale (defined as dimension ratio of $D$ to $B$ in Figure 2) are adopted 1/2, 1 and 2 respectively.

#### 3.2. Calculation parameters

The calculation parameters of the ground are listed in Table 1.

| Stratum                        | Gravity (kN/m$^3$) | Modulus of elasticity (GPa) | Poisson's ratio | Cohesion (MPa) | Internal Friction angle (°) |
|-------------------------------|-------------------|-----------------------------|-----------------|----------------|-----------------------------|
| Intensely weathered granite   | 22.3              | 1.5                         | 0.4             | 0.125          | 23.5                        |
| weakly weathered granite      | 24.5              | 3.65                        | 0.3             | 0.45           | 33                          |
| Slightly weathered granite    | 25.7              | 20.0                        | 0.25            | 1.5            | 50                          |

### 4. Analysis of Calculation Results

#### 4.1. Safety Factor Distribution

The safety factors of all the calculation cases are listed in Table 2.
Here $F_s < 2$ is defined as the strongly influence zone, while $F_s$ greater than peak safety factor is defined as non-influence zone. The weak influence zone is between strong influence zone and non-influence zone. By using Kriging interpolation, Figure 3 can be obtained from Table 2. It can be seen that the influence partition shows the similar shape under the three different relative scale cases.

| Relative scale | Angle position | Point 1 | Point 2 | Point 3 | Point 4 | Point 5 |
|---------------|----------------|--------|--------|--------|--------|--------|
| D/B=1/2       | 0°             | 1.87   | 2.29   | 2.25   | 2.25   | 2.26   |
|               | 30°            |        | 4.29   | 4.48   | 4.31   | 3.98   |
|               | 60°            | 1.83   | 3.87   | 4.13   | 3.96   | 3.62   |
|               | 90°            | 1.65   | 2.90   | 3.83   | 3.89   | 3.59   |
|               | 0°             | 2.16   | 2.22   | 2.23   | 2.23   | 2.23   |
| D/B=1         | 30°            |        | 4.63   | 5.19   | 5.19   | 3.98   |
|               | 60°            | 1.62   | 3.59   | 3.98   | 3.98   | 3.61   |
|               | 90°            | 1.54   | 2.70   | 3.59   | 3.79   | 3.54   |
|               | 0°             | 1.56   | 2.11   | 2.28   | 2.28   | 2.28   |
| D/B=2         | 30°            |        | 3.54   | 4.29   | 4.27   | 3.88   |
|               | 60°            | 1.54   | 3.37   | 3.78   | 3.82   | 3.59   |
|               | 90°            | 1.53   | 2.68   | 3.53   | 3.72   | 3.49   |
4.2. Influence of Relative Scale

$H_{qr}$ and $H_{rw}$ are defined as the threshold of strong to weak influence and weak to none influence in vertical direction respectively, while $S_{qr}$ and $S_{rw}$ are defined as the threshold of strong to weak influence and weak to none influence in horizontal direction respectively. Based on the thresholds vary under different relative scale in Figure 3, the relationship curves were established by using linear fitting, shown as in Figure 4.

The fitting equation of $S_{qr}$, $S_{rw}$, $H_{qr}$ and $H_{rw}$ are listed below:

\[
S_{qr} = 2.5714 \frac{B}{D} + 1 \quad (3)
\]

\[
S_{rw} = 2.5714 \frac{B}{D} + 1 \quad (4)
\]

\[
H_{qr} = 1.2857 \frac{D}{B} + 7.5 \quad (5)
\]
\[ H_{rw} = 2.7143 \frac{B}{D} + 15.5 \]  

(6)

4.3. Influence partition Map

Based on the above results, and considering the convenience use on site, a influence partition map of tunneling adjacent to multi-storey building in upper-soft and lower-hard stratum has been proposed, which is composed of some simple lines, as shown in Figure 5.

![Influence partition map of tunneling adjacent to building in upper-soft and lower-hard stratum](image)

The above influence partition map can be drawn in three steps, as follows:

(1) Determine \( S_{qr} \) and \( S_{rw} \) according to \( D/B \) first, then draw IK, LM, PQ, RT lines according to the fracture angle of \( 45^\circ + \varphi/2 \), the intersection of IK and the boundary line of strong weathering layer is at point J, the intersection of RK and the boundary line of strong weathering layer is at point S.

(2) Determine \( H_{qr} \) and \( H_{rw} \) according to \( D/B \) first, then to determine position of point N and O. Determine the arc from three points of J, N, and S, which intersect LM and PQ at point M and Q respectively.

(3) Draw the concentric arc of the arc JNS from the point O, the IK and RT are respectively intersected with the arc to the K and T points.

5. Conclusion

(1) The distribution of safety factors in three cases with relative scale of 2, 1, \( 1/2 \) was obtained, and divide influence zone under the multi-storey building in upper-soft and lower-hard stratum with the safety factor. The safety factor of 2.0 was defined as the boundary of the strong to weak influence zone, and the peak safety factor was considered as the boundary of weak to none influence zone. The influence partition shows the similar shape under these three different relative scale of 1/2, 1 and 2.

(2) The quantitative relationship between the safety threshold and the relative scale was fitted, and the index equation of the influence partition was obtained. Based on the simple and practical principle, general influence partition map of tunneling adjacent to the multi-storey building in upper-soft and lower-hard stratum was established by several simple lines.

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