Sub-model stress analysis for construction process of a metro crossing passage tunnel with shield machine

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Abstract—This paper aims to simulate and optimize the structure stress during the construction process of a metro crossing passage tunnel with shield machine. Taking the world first metro crossing passage tunnel with shield method at Ningbo Metro Line 3 as an example, a finite element analysis model is developed to simulate the construction process. To achieve accurate results in some key structural components local sub-model approach is applied for some of sub-structures. The results obtained from the present finite element analysis are found to match well with the strain test monitoring data of the concrete segments. The obtained results also show that the maximum stress occurs at the T-joint of the starting and receiving sections during the construction process. With the progress of the construction, the stress at the T-joint of the starting section is gradually reduced, while the stress at the T-joint of the receiving section is gradually increased. Consequently, an authentic, reliable and advanced simulation process is established, which could provide technical support for the optimization of the construction process of metro crossing passage tunnel.

1. Introduction
The development of underground transportation is one of the effective ways for urban public transports, particularly for large cities. In recent years, there is a rapid development of subway rail transit systems in China to cope with the increased population in cities and to release the urban traffic issues. In the construction of subway rail transit, the metro crossing passage is widely used as a life-saving passage in case of emergency (Ding et al., 2014). To construct the metro crossing passage tunnel, the freezing method using traditional excavation technique is often used (Lai et al., 2018; Liu et al., 2018; Yang et al., 2019). Many studies have been carried out on the construction performance when the freezing method is used (Hu et al., 2018; Lv et al., 2019; Tang and Li, 2018). Despite its many advantages, the freezing method has its weakness such as high cost and time consuming. Moreover, the freezing method can be used only as a temporary soil reinforcement treatment. Thus, its effective time is very limited, which restricts the excavation process (Ieronymaki et al., 2018; Shang et al., 2004; Wang et al., 2016).

In contrast to the freezing method, the shield method provides an attractive alternative (Mo and Chen, 2008; Zhang et al., 2015). The shield method is commonly used for the construction of underground tunnels in soft soil areas. Since the early 18th century the shield method has been gradually applied to subways, railways and coal mine projects due to its construction convenience, high efficiency and good safety (Berthoz et al., 2018; Hasanpour, 2014; Hasanpour et al., 2018). Many successful projects have been reported on the use of shield method in subway tunnels (Sun et al., 2012). The use of the finite element method for the analysis of tunnel construction problems has
increased notably. However, the vastness of choices in modelling procedures, which include the constitutive model, mesh, parameters and boundary conditions, tend to produce results that are user-dependent and often limited in the aspects they can reproduce from real cases or physical models. Duddeck (1991) provided a review on the early application of numerical methods in tunnelling, the achievements and the shortcomings. Bernat et al. (1999) developed a model for describing the excavations of the Lyons-Vaise metro by calibrating the partial stress release factors of an unlined tunnel with the measured tunnel crown displacements.

2. Project overview and construction method

Figure 1 shows the overall structure of the entire tunnel at Ningbo Metro Line 3. The entire tunnel is a symmetrical structure, consisting of two subway tunnels and a metro crossing passage tunnel. The subway tunnel part is made up of three sections with 1.5 m each in longitudinal direction. Each section consists of a steel segment and a reinforced concrete segment. The metro crossing passage tunnel consists of two ring beams at each end, four ring steel segments with two at each end, and nineteen ring reinforced concrete segments. The segment thickness of the metro crossing passage tunnel is 0.25 m.

3. Numerical simulation

3.1. Finite element model and its boundary conditions

3.1.1. Global model

The global model consists of the entire tunnel plus the nearby soil layer, as shown in Fig.2a. The dimensions of the global model are 82.5 m × 4.5 m × 30.8 m in x, y and z directions, respectively. The depth of the subway tunnel is 12.3 m and the length of the metro crossing passage tunnel is 17 m. A free boundary condition is applied at the top surface, while a fixed constraint is used at the bottom surface. Normal direction constraint is applied at the remaining boundaries. In addition, the ground stress and the effects of excavation and tunnel support system are also considered during the construction process.

Fig.2 shows the simplified model of the entire tunnel. In the simplified model the concrete
segments and the steel segments of the subway tunnel are simplified into one unit. The one ring beam and the two steel segments of the passage tunnel are simplified into one unit. Taking into account both the excavation process and the convergence of the finite element analysis, the metro crossing passage tunnel, which consists of 19 ring concrete segments, is divided into three parts. In the order from right to left, these three parts are 1-ring to 6-ring, 7-ring to 13-ring, and 14-ring to 19-ring concrete segments, respectively.

3.1.2. Sub-structure models
The sub-structure model is the part of the global model. Fig. 3a shows one of the sub-structure models used, which has the dimensions of 25.85 m × 4.5 m × 8.8 m in x, y and z directions, respectively, which includes the entire tunnel, while the steel segments, concrete segments and ring beams in it are refined. Fig. 3b shows the refined sub-structure model of the entire tunnel. During the analyses, the displacement boundary conditions of the sub-structure models are provided by the data obtained from the analysis of the global model.

3.2. Case setting
Firstly, the global model is analyzed, and the ground stress balance calculation (case 0) is completed before the subway tunnel excavation. Then the excavation of the subway tunnel and the laying of the segments (case 1) are simulated. Afterwards, the construction process of the metro crossing passage tunnel (case 2 to case 7) is analyzed, which includes supporting, excavation and laying segments.

Meanwhile, the sub-structure models are analyzed after the results of the global model are obtained. The analysis results of the 7 global model cases are used as the boundary condition for the simulation of the sub-structure models. Fig. 5 shows the case diagram for the construction process of the metro crossing passage tunnel based on the shield method. Table 1 provides the notes of all cases in the
construction process of the metro crossing passage tunnel.

| Case  | Detailed description of cases                                                                 |
|-------|-----------------------------------------------------------------------------------------------|
| Case 0| Initial state of ground stress balance when the subway tunnel is not excavated.               |
| Case 1| The subway tunnel is excavated, its segments are laid, but the metro crossing passage tunnel is not excavated. |
| Case 2| The shield machine starts to support at the starting section and excavates the metro crossing passage tunnel. One ring beam and two ring steel segments are installed at the starting section. |
| Case 3| The 6-ring reinforced concrete segments are installed.                                         |
| Case 4| The 13-ring reinforced concrete segments are installed. The shield machine starts to support at the receiving section. |
| Case 5| The 19-ring reinforced concrete segments are installed.                                         |
| Case 6| One ring beam and two ring steel segments are installed at the receiving section. The shield machines are not removed at the starting and receiving sections. |
| Case 7| The shield machines are removed at the starting and receiving sections.                         |

4. Results and discussion

4.1. Strain monitoring of concrete segments during construction

24 testing points were put at the concrete segments of the starting and receiving sections. Fig. 6 shows the distribution of these measure points. Of 24 points, however, only 5 points give valid test results, while the rest points were damaged during the construction process. Table 2 lists the test strain results of concrete segments in various cases.

| Monitoring points | Case 2  | Case 3 | Case 4  |
|-------------------|---------|--------|---------|
| 33-6              | Lost    | -0.56  | 7.5     |
| 33-7              | Lost    | -1.51  | -2.8    |
| 33-8              | Lost    | -3.2   | Lost    |
| 33-9              | Lost    | -0.75  | -2.33   |
| 33-10             | Lost    | -6.57  | 2.1     |
| 38-16             | -1.5    | Lost   | -3.8    |

4.2. The comparison of simulation results and test data

Table 3 shows the comparison of the strain results at the concrete segments between the test and simulation for the case 2, 3 and 4. It can be seen that, the simulation results match with the test data approximately. Therefore, the stresses obtained from the global model and sub-structure models for the construction process can reflect the actual stress status of the structural system.
### Table 3 Strain results of concrete segments in various cases (in m)

| Monitoring points | Case 2 | Case 3 | Case 4 |
|-------------------|--------|--------|--------|
|                   | Test data | Simulation data | Test data | Simulation data | Test data | Simulation data |
| 33-6              | Lost    | -0.56  | -0.76  | 7.5       | 5.9       |
| 33-7              | Lost    | -1.51  | -1.6   | -2.8      | -2.7      |
| 33-8              | Lost    | -3.2   | -3.1   | Lost      |           |
| 33-9              | Lost    | -0.75  | -0.73  | -2.33     | -2.73     |
| 33-10             | Lost    | -6.57  | -6.05  | 2.1       | 1.75      |
| 38-16             | -1.5    | -1.1   | Lost   |           | -3.8      | -3.9      |

### 4.3 Stress analysis of the construction process

The construction process of the metro crossing passage tunnel with shield machine mainly includes six cases from case 2 to case 7. Fig. 7 shows the stress contours of the metro crossing passage tunnel in various cases. As can be seen from Fig. 7, during the construction process, the stress of the overall structure is generally small, and thus the construction structure is safe. The maximum stress occurs at the T-joint steel segment of the starting sections for case 2 to case 4, at which No. 13 ring concrete segment is completed. The maximum stress location moves to the T-joint steel segment of the receiving section for case 5 to case 7, at which No. 19 ring concrete segment is installed and the shield machines are removed at the starting and receiving sections.

![Fig. 7 The stress contours of the metro crossing passage tunnel in various cases.](image)

Table 4 gives the stress values at the T-joint steel segments of the starting and receiving sections. Fig. 8 shows the stress variation at the T-joint of the starting and receiving sections. As can be seen from Table 4 and Fig. 7, during the progress of the construction, the stress at the T-joint of the starting section is gradually reduced, while the stress at the T-joint of the receiving section is gradually increased.

### Table 4 Stress values at the T-joint of starting and receiving sections (in MPa)

| Case    | Stress value at T-joint of the starting section | Stress value at T-joint of the receiving section |
|---------|-------------------------------------------------|-------------------------------------------------|
| Case 2  | 156.4                                           | 136.2                                           |
| Case 3  | 156.0                                           | 138.5                                           |
| Case 4  | 146.9                                           | 140.1                                           |
| Case 5  | 144.2                                           | 160.1                                           |
5. Conclusion
In this paper, a finite element analysis model has been developed for analyzing a metro crossing passage tunnel with shield machine. The numerical simulation has been conducted by combining global- and sub-structure models. The simulation models also include the curved bolts, which have a significant influence on the stress transfer between segments. From the obtained results, the following conclusions can be drawn,

1. The maximum stress occurs at the T-joint steel segment of the starting and receiving sections during the construction process. The T-joint should be strengthened during the construction process.
2. As the progress of the construction, the stress at the T-joint of the starting section is gradually reduced, while the stress at the T-joint of the receiving section is gradually increased.
3. The simulation results match well with the strain test data of the concrete segments, which demonstrates that the present analysis models and procedure could deliver an accuracy stress result for the construction process.
4. The CAE simulation process presented in this paper can monitor the safety of the metro crossing passage tunnel, and it can provide technique support for the optimization of the construction process of metro crossing passage tunnel.

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