The numerical analysis of the cross passage of large diameter shield tunnel beneath the river

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Abstract. The construction of the cross passages of twin shield tunnel is confronted with high uncertainty and huge risk. Ground freezing method is widely used for passages excavation in sandy ground condition when the tunnel is under the water. Earlier studies usually concerned the effectiveness of the freezing program, such as the space between the freezing pipes or the temperature variation in the frozen soil. In this paper, the structure force of the cross passage of a large diameter shield tunnel beneath the river is discussed. A 3-dimensional numerical method is described to calculate the stress of the frozen soil and the internal force of the cross passage lining. The critical situations in construction and operation phases and the key mechanical parts are recognized. The safety of the design scheme is checked.

1. Introduction
As a part of the tunnel fire life safety strategy, cross passages are required to connect twin tunnels in the metro and highway tunnel project. In the Code for design of metro[1], it is suggested that the distance of two cross passage is not larger than 600 meters. In the city of Shanghai, Guangzhou, Nanjing, Wuhan in China, many metro tunnels are built cross rivers. There are plenty of cases and studies[2-5] in the construction of cross passage in metro shield tunnels whose diameters are nearly 6 meters. In the highway shield tunnels, in which the diameters are 10 meters or more, the risk of construction of cross passages under the river is much larger, such as Shanghai Yangtze River tunnel[6], Wuhan Yangtze River tunnel[7]. Although in nowadays, the ground freezing method is widely used in the construction in cross passage, the risk in construction is still high. In this field, most earlier studies focus on the closure of freezing wall. Zhou[8] compare the thickness of the freezing wall calculated by numerical method and measured from the site. Yang[6] have analysed the development rules of the frozen soil and suggested an optimized freezing program. In this paper, the mechanic safety of a large diameter shield tunnel is discussed. We assume that the freezing wall is worked. The safety of the shield tunnel segments, lining of the cross passage and the strength of the frozen soils are checked by using 3D finite element analysis. It is noted that the design scheme in this paper is not final in the project.

2. Background of Project

2.1. Project Overview
The Project of Multi-lane Road Tunnel under the River Karnaphuli, Chittagong - Bangladesh is located in Chittagong, connecting the east and west banks of the River Karnaphuli, with the shield tunnel length of 2925 meters. The diameter of the tunnel is 11.8m. The thickness of the shield tunnel segment is 500mm. Three connecting channels of the shield tunnel section are to be built respectively to meet the design requirements and the needs of disaster prevention and rescue. The clear distance of the twin
tunnel is nearly 12m. The 400mm thick concrete lining is used as the lining of the cross passage, with its inner diameter of 3.4m.

2.2. Geological, hydro-geological and site feature
The tunnel is located at the mouth of the Karnaphuli river. Based on regional geological data and survey data the strata from top to bottom are Stratum ②-mucky silty clay(Q₄m₃), Stratum ③1-silty clay(Q₄m₃), Stratum ③6-silty sand(Q₄m₃), Stratum ③8-silty sand(Q₄m₃), Stratum ④-silty and fine sand(Q₄m₃). The 1# and 3# cross passages are at the stratum under the east bank and the west bank. The 2# cross passage is located beneath the river. The overburden thickness of the tunnel at cross passage is 25~28m. The 1# and 2# cross passages are located in the ④ stratum, The 3# cross passage is located in the ③8 stratum. The permeability and the head of the stratum is quite high.

2.3. Design of cross passage and freezing program
Artificial freezing method is widely used in the construction of cross passage in water-rich sandy stratum to proof the water and afford support during excavation. In this project the flat profile of tunnel structure is shown in the Figure 1. Outside the cross passage the thickness of frozen soil is not less than 3.1m (2.5m at the strengthened end). There are 44 frozen hole with a total length of 569.6m. The maximum spacing for hole forming of outer-ring frozen hole is 1.04m to insure the closure of the frozen wall. As is shown in Figure 1, the thickness of the cross passage is 0.4m. At the end of the cross passage which is connecting with the main tunnel, a strengthened section with length of 2.3m is designed. The thickness of the strengthen section is 0.7m.

Figure 1. Flat profile of the tunnel and cross passage structure.

Two steel frames are installed as a supporting system for the adjacent segments during freezing and excavation, which is shown in Figure 2. The jacking force of the jack shall be adjusted according to the deformation of the segment so as to resist the influence of frost expansion and excavation on the tunnel.

Figure 2. Supporting system of steel frames on the adjacent segments.
3. Numerical model

3.1. Model calculation and assumption
A widely used commercial geotechnical software Plaxis 3D is employed to complete the finite element analysis. As is shown in Figure 3 and Figure 4, there are some assumptions adopted in the model. Since the affected area is small, all strata are distributed horizontally within the calculating area of the project location. Two tunnels are assumed to be in the same elevation. Assuming the model is axisymmetric along the plane in the middle of the horizontal channel, a quarter of the model is taken and established to reduce the element quantity of three-dimensional numerical analysis.

3.2. Element type and parameters of numerical model
The soil volume is modeled by means of 10-node tetrahedral element, include the soil in situ and the frozen soil. The reinforced concrete segments of shield tunnel and the lining of the cross passage are modeled by 2D plate elements. The hardening soil model is used for natural stratum. The parameters of the soil layers are shown in Table 1.

| Stratum name                 | CU test c | CU test φ | \(E_{ooed,ref}\) | \(E_{soe,ref}\) | \(E_{oor,ref}\) | Poisson's ratio \(\nu\) | Exponent \(m\) |
|-----------------------------|-----------|-----------|----------------|----------------|----------------|-------------------|----------------|
| ① Mucky silty clay         | 11.2      | 5.2       | 5.1            | 8.5            | 15.5           | 0.4               | 0.8            |
| ② Silty sand               | 5.4       | 31.1      | 14.7           | 14.7           | 44.3           | 0.3               | 0.6            |
| ③ Fine sand                | 0.1       | 30.6      | 14.7           | 14.7           | 44.3           | 0.3               | 0.9            |
| ④ Mucky silty clay         | 7.2       | 4.5       | 2.8            | 5.2            | 8.3            | 0.35              | 0.85           |
| ⑤ Fine sand                | 4.6       | 32.7      | 18.4           | 18.4           | 55.3           | 0.29              | 0.6            |
| ⑥ Silty clay               | 12.6      | 4.3       | 2.9            | 5.5            | 8.6            | 0.4               | 0.85           |
| ⑦ Silty and fine sand      | 0.1       | 34        | 25             | 25             | 75             | 0.28              | 0.65           |
| ⑧ Fine sand                | 0.1       | 35.5      | 28             | 28             | 84             | 0.28              | 0.6            |

The linear elastic model is adopted for the stratum of the freezing circle. According to the physical and mechanical properties of frozen soil test report, the values of elasticity modulus of silty and fine sand are 100MPa, 139MPa and 243MPa respectively at -5°, -10° and -15°, and the values of Poisson's
The design freezing temperature is -13°, so the elasticity modulus of frozen silty and fine sand is 201 MPa and the Poisson’s ratio is 0.21 by interpolation.

### 3.3. The simulation of construction processes

The construction processes are simulated as follows: (1) ground stress equilibrium, (2) shield tunnel excavation, (3) artificial ground freezing, (4) shield segments opening, (5) excavation of frozen soil in the cross passage, (6) construction of the lining of the cross passage, (7) unfreezing the frozen soil. In step 3, the material characters of freezing circle are changed from natural stratum to frozen soil and then in step 7 they are change back to simulate the freezing and unfreezing process.

### 4. Calculation results

In the structure design there are several critical phases in which the shield tunnel segments and the cross passage lining are in the most dangerous. The first one is the step that excavation of frozen soil in the cross passage. In this phase the frozen soil bear all the load caused by excavation. The principal total stress in the frozen soil is shown in Figure 5. It is worth noting that the circle between the frozen soil excavation and the lining is subject to stress concentration due to unit division and geometrical shape problems, so it is not considered temporarily. From Figure 5(a) it is shown that the maximum compressive stress in the frozen soil is 1.4 MPa which is yellow at the middle of the excavation channel. The maximum tensile stress which is shown in Figure 5(b) is 0.16 MPa.

#### Table 2. safety assessment of frozen soil curtain of connecting channel

| Item              | Compressive/bending tensile stress (MPa) | Shear stress (MPa) | Displacement (mm) |
|-------------------|-----------------------------------------|--------------------|-------------------|
|                   | \(\sigma_1\) (Maximum compressive stress) | \(\sigma_3\) (Maximum tensile stress) | \(\tau_{\text{max}}\) | \(U_{\text{max}}\) |
| Calculated value  | 1.4                                     | 0.16               | 0.65              | 17.9              |
| Strength index    | 4                                       | 1.8                | 1.5               |                  |
| Safety coefficient| 2.85                                    | 11.25              | 2.3               |                  |
| Location          | Both waists inside the frozen circle     | Upside of variable section of frozen circle | Both waists inside the frozen circle | Bottom plate of midsection |
The safety assessment of the frozen soil curtain is shown in Table 2. From the table, it is shown that the bearing capacity or strength of the frozen soil curtain can meet the requirements (the safety coefficient of compressive strength is not less than 2.0, that of buckling strength is not less than 3.0, and that of shear strength is not less than 2.0). The displacement of the frozen soil curtain is 17.9mm, which is also accepted.

During the construction phase, the safety of the opening ring of the main shield tunnel is guaranteed by temporary steel frames and temporary support of the adjacent rings. While the safety of the cross passage itself is guaranteed by frozen soil in the freezing circle. But in the operation period, after the frozen soil is thawed and the supporting frames are removed, the strengthened end of the cross passage (also known as bell mouth) is the critical section whose strength needs to be checked.

Since the opening ring and the adjacent ring are mainly connected by bolts, both shear resistance and rigidity are small. Moreover, in the strengthened end of the cross passage, steel bars are embedded in the opening segment of the main tunnel, and are poured into a monolithic structure, which is shown in Figure 6. Therefore, in the analysis, we assume that the axial force of the opening ring at the opening is completely borne by the strengthening section of segment ends of the cross passage.

According to calculation of main tunnel, axial force of the segment in the multi-lane road tunnel under soil-water pressure is calculated, as is shown in Figure 8. Before the presence of opening, axial forces at upper and lower parts of the opening ring are approximately $N_{\text{up}}=3100\text{kN/m}$ and $N_{\text{down}}=3440\text{kN/m}$. The Forces can be divided into two directions—horizontal and vertical directions according to directions of acting forces. As is shown in Figure 7, at last the force of $N_{\text{v,up}}=2752\text{kN/m}$ and $N_{\text{v,down}}=3240\text{kN/m}$ is loaded at the up and down plate of the strengthened end to simulate the force of the main tunnel segments at the opening ring.

![Figure 6. Details of the strengthened end of the cross passage.](image6)

![Figure 7. The load on the strengthened end in the numerical model.](image7)

![Figure 8. Axial force in the segments of the main shield tunnel.](image8)
In this situation, the moments of two directions of the strengthened end is shown in Figure 9. As is shown in the Figure 9(a), taking no account of stress concentration caused by FEM modeling, the maximum bending moment of the strengthened end along the axis of the cross passage is 1,000 kNm/m, located above the end door of the cross passage, where axial force is around 500kN/m. The bending capacity meets the requirement with thickness of 700mm and 38 pieces of φ25 steel bars in 2m width. The maximum circumferential bending of strengthened end of the cross passage is 875kNm/m, which is shown in Figure 9(b). The bending capacity in the direction also meets the requirement.

![Figure 9. The moments of the strengthened end in two direction.](image)

The axial forces of the opening segments are broken into vertical and horizontal forces. Vertical force causes bending moment at lining end of cross passage and is checked above. Horizontal force produces axial force at the lining end of the cross passage, and mainly supported by embedded bars in the segment of main tunnel, which is shown as No.24 steel bars in Figure 6. The horizontal force obtained from the axial forces is 2581kN in total, which is borne by 128 pieces of steel bars with the diameter of 25 mm. The shear stress of each reinforcement is 41 MPa, which is much less than shear strength of reinforcement. So the safety of horizontal direction of the lining at the strengthened end is also ensured.

5. Conclusion
A three dimensional numerical method is suggested to check the structure safety of cross passage in a large diameter shield tunnel under water. A quarter of the model is adopted to reduce the element quantity for symmetry. Two critical situations are recognized, one is in construction and the other is in operation. In the construction phase, the compressive stress, tensile stress and shear stress of the frozen soil are checked. In the operation phase the internal force of the strengthened end of cross passage lining and shear stress of the embedded bars are calculated. The bearing capacity of the cross passage structure and frozen soil meet the requirement both in the construction period and in the operation period.

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