Study on Water/mud Inrush of Tunnel Inclined Shaft Based on Material Point Method

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Abstract. Water/mud inrush is a serious threat to the safety of tunnel construction. It is very important to set up a certain thickness of aquifuge to prevent water/mud inrush and eliminate the catastrophe causing object when there exists potential risk of water inrush in front of the tunnel face. Taking the water inrush accident of No.1 ventilation inclined shaft at K21+693 in Yingpanshan Tunnel as an example, the cause of water inrush is analysed from angle of the geological and hydrological conditions. Then, a minimum aquifuge thickness of the tunnel face valuing 8.6m is obtained based on the thin elastic plate theory model. In order to explore the mechanism of water/mud inrush near the water-bearing fault, the numerical models of the aquifuge with a thickness of 10m/5m/1m were established based on the material point method. The results show that it is reasonable to take 10m as the construction safety thickness, and the water/mud inrush mechanism varies with the aquifuge thickness. The overall extrusion failure occurs when the aquifuge is thicker, and the middle fracture failure occurs when the thickness is thinner. The material point method has advantages in studying large deformation problems including water/mud inrush. The results provide references for strengthening aquifer, eliminating catastrophe causing object and ensuring construction safety.

Keywords: Water/mud inrush, Minimum aquifuge thickness, Thin circular plate theory, Failure mechanism, Material point method (MPM)

1. Introduction
Tunnel driving construction is now facing various challenges. Large deformation, collapse, rock burst, water/mud inrush and other disasters tend to occur due to the complexity of geological conditions. At present, water/mud inrush is still one of the main geological disasters in tunnel construction [1]. It has seriously affected the safety of project, resulting in construction delays and even casualties [2].

Recently, a lot of research have been conducted on the mechanism of tunnel water/mud inrush. Liu et al. and Jiang et al., analysed the mechanism of water inrush in aquifer parallel to the tunnel [3-4]; Zhang et al. and Zhang et al. divided the causes of water inrush into four cases: tensile failure of aquifuge, shear failure of aquifuge, hydraulic expansion of fracture and instability of key rock blocks [5-6].
Research shows that the mechanism of water/mud inrush was tensile failure in the lower part of the tunnel face [7]. However, these analyses of water inrush mechanism above are mainly qualitative description, quantitative analyses are expected to reveal the characteristics of the failure process. The FEM simulation cannot demonstrate the failure process of water inrush, in order to directly observe the failure process and explore the failure mechanism, numerical models of aquifuge near fracture zone are respectively built based on material point method (MPM). The structure of this paper is as follows. Section 2 introduces the project briefly and analyses the causes of water inrush in inclined shaft from the angle of geological and hydrological conditions of Yingpanshan tunnel. Section 3 deduces the minimum aquifuge thickness of the project based on thin elastic circular plate model. Section 4 establishes numerical models based on material point method to analyse the mechanism of water/mud inrush and verifies the rationality of the analytical safety thickness model. The last section is conclusion.

2. Project background
Yingpanshan Tunnel, one of the control projects of Huali expressway, is an extra-long tunnel about 11300m long. The maximum buried depth of the tunnel is about 883.395m, equipped with No. 1 and No. 2 ventilation inclined shafts. The engineering geological profile near the No. 1 inclined shaft where water gushing occurred is shown in Figure 1.

Figure 1. Tunnel engineering geological profile.

According to the geologic survey report, the influence range of the F2 fault fracture zone near the inclined shaft is 100 meters from K21+890 to K21+990. The area affected by the fault is consisted of strongly weathered argillaceous sandstone and karst fissure water is developed in the fracture zone. The excavation of the inclined shaft leads to the gradual decrease of the aquifuge thickness on tunnel face, which is not enough to withstand the groundwater pressure, leading to the occurrence of water inrush.

3. Minimum aquifuge thickness model
3.1. Analytical model of thin circular plate

The aquifuge is simplified as a circular thin plate, and the mechanical analysis is carried out on the basis of the thin elastic plate theory, and the groundwater is regarded as the external uniform load acting on the tunnel face. Then the analytical model of the critical aquifuge thickness is deduced.

![Mechanical model of circular thin plate](image)

Figure 2. Mechanical model of circular thin plate.

The mechanical model is shown in Figure 2. The periphery of the circular thin plate is regarded as a fixed end, which is subjected to water pressure uniformly distributed load. The element is analysed in polar coordinates, and the stress formula can be obtained from elasticity as follows [8]:

\[
\begin{align*}
\sigma_r &= \frac{3}{4} \frac{q z}{t^3} \left[ (1 + \mu) R^2 - (3 + \mu) r^2 \right] \\
\sigma_\theta &= \frac{3}{4} \frac{q z}{t^3} \left[ (1 + \mu) R^2 - (1 + 3\mu) r^2 \right]
\end{align*}
\]

(1)

Where, \(\sigma_r\) is the radial stress of the rock plate, \(\sigma_\theta\) is the circumferential stress of the rock plate, and \(z\) is the distance in the direction of the thickness of the rock plate.

At the center of the tunnel face, \(r = 0\), according to formula (1)

\[
(\sigma_r)_{r=0} = (\sigma_\theta)_{r=0} = \frac{3}{4} \frac{q z}{t^3} (1 + \mu) R^2
\]

(2)

At the edge of the tunnel face, \(r = R\)

\[
\begin{align*}
\left| (\sigma_r)_{r=R} \right| &= \frac{3}{2} \frac{q z R^2}{t^3} \\
\left| (\sigma_\theta)_{r=R} \right| &= \frac{3}{2} \frac{\mu q z R^2}{t^3}
\end{align*}
\]

(3)

Since Poisson's ratio is smaller than 1, it is obvious that the maximum stress occurs at the edge of the tunnel face.

\[
\sigma_{\text{max}} = (\sigma_r)_{r=R} = \frac{3}{4} \frac{q R^2}{t^2}
\]

(4)

\[
t = R \sqrt{\frac{3q}{4|\sigma|}}
\]

(5)

Where, \(|\sigma|\) refers to the tensile strength of aquifuge.

Considering that the rock mass of the tunnel face contains joints and cracks, this will reduce the strength of the face to a certain extent. The thickness of the aquifuge calculated by formula (5) is actually unsafe.

3.2. Calculation of minimum aquifuge thickness
Referring to the construction drawings of this project, it is found that the radius of No.1 inclined shaft is 5m, the aquifuge is strongly weathered argillaceous sandstone classified as grade IV, whose tensile strength is 2.66MPa, the buried depth of the inclined shaft is about 530m, and the saturated density of the soil in the fracture fault zone is 20kN/m$^3$.

$$q = \gamma_d \cdot h = 20 \times 530 = 10600 \text{ KPa}$$

According to formula (5), the minimum aquifuge thickness of No.1 inclined shaft is as follows.

$$t = R \sqrt{\frac{3q}{4|\sigma|}} = 5 \times \frac{3 \times 10600}{4 \times 2660} \approx 8.64m$$

The actual thickness of aquifuge in water inrush area is about 10 m, which is pretty close to calculated results above. The results indicate that the minimum aquifuge thickness based on thin circular plate theory is reasonable. The error is mainly caused by cracks in rock mass.

Considering that this formula is suitable for rock mass with good integrity, which is actually unsafe. Therefore, the construction safety thickness in this project is set as 10m.

4. Numerical model based on MPM

4.1. Material point method

Material point method (MPM) is a new numerical method suitable for large deformation problems [9]. It solves and updates the motion information on the background grid to ensure that the particles do not penetrate each other when move, so as to automatically satisfy the contact condition [10]. The calculation process is divided into five steps (Figure 3).

1. Initialization of grid and material points.
2. Material point quantities are extrapolated to grid nodes.
3. Equations of motion are solved on the grid.
4. Derivative terms are extrapolated back to material points.
5. Resetting of grid.

![Figure 3. Calculation process of MPM.](image)

In this paper, three-dimensional water inrush models are established using the numerical simulation software Anura3D based on the material point method.

4.2. Model parameters

The profile of the inclined shaft is approximately a circle with a diameter of 10m, and the thickness of the aquifuge is considered as 1m, 5m and 10m respectively. A 5m fracture zone behind the aquifuge is built as the disaster object. Fully constraints are set on the circumferential surface of the model, and a uniform load is applied to the part of the fracture zone to simulate the pore water pressure. Taking the 5m aquifuge as an example, the numerical model is shown in Figure 4.
Figure 4. Numerical model of material point method.

The material parameters of aquifuge and fault fracture zone are shown in Table 1.

Table 1. Parameters for MPM models.

| Parameter                      | Unit   | Sandstone(IV)          | ffz          |
|--------------------------------|--------|------------------------|--------------|
| Material type                  |        | Saturated material -   | Saturated material - |
|                                |        | fully coupled           | fully coupled |
| Density liquid                 | kg/m³  | 1000                   | 1000         |
| Bulk modulus liquid            | kPa    | 2.15 *10⁴              | 2.15 *10⁴   |
| Dynamic viscosity liquid       | kPa/s  | 1.002*10⁻⁶             | 1.002*10⁻⁶  |
| Initial porosity               | -      | 0.2                    | 0.4          |
| Solid density                  | kg/m³  | 2650                   | 2000         |
| K₀-value                       | -      | 0.5                    | 0.5          |
| Intrinsic permeability         | m²     | 1.0214*10⁻⁹            | 1.0214*10⁻⁹ |
| Material model solid          |        | Mohr-Coulomb           | Mohr-Coulomb |
| Young’s modulus                | kPa    | 2*10⁶                  | 1.2*10⁶     |
| Poisson ratio                  | -      | 0.35                   | 0.4          |
| Cohesion                       | kPa    | 250                    | 25           |
| Friction angle                 | °      | 30                     | 10           |
| Dilatancy angle                | °      | 0                      | 0            |
| Tensile strength               | kPa    | 2260                   | 0            |

The computation method is set as MPM-mixed integration, the loading step is 100 and the critical time step is 0.02s. The courant number is set as 0.98 to stabilize the calculation, and the gravity in the negative direction of y axis is applied. In order to converge to the quasi-static solution an overall local damping coefficient for all active elements of 0.05 is applied.

5. Results and discussions

5.1. Verification of minimum safe thickness

According to the numerical simulation results, the strain and longitudinal displacement of the 10m aquifuge are shown in Figure 5, and the effective stress variation curves at the bottom of the tunnel face (ID=0) and the center of the tunnel face (ID=1) are shown in figure 5.
It is obvious in Figures 5 that the strain of the rock mass at the edge of the tunnel face is larger while the longitudinal displacement at the center of tunnel face is larger. There is no obvious deformation at the tunnel face. According to Figure 6, the magnitude displacement at the center of tunnel face increases slowly while the velocity decreases, and finally the displacement reaches a stable value of 0.13 m when the structure reaches static equilibrium.

To conclude, it is reasonable to set the construction safety thickness to 10 m in this project.

5.2. Water inrush process

While the thickness of aquifuge is less than construction safety value, water inrush accidents tend to occur immediately. To study the influence of aquifuge thickness on disaster developing process, the strain and longitudinal displacement of the aquifuge with thickness of 5 m as well as 1 m are shown in Figure 7.
Figure 7. Strain & displacement cloud diagram.

It can be seen from Figure 7 that the failure process varies with the thickness of the aquifuge. When the aquifuge is thicker, the failure process is relatively slow, manifested as overall extrusion failure; when the thickness is relatively small, the failure process develops rapidly and the range of influence is large, showing as the intermediate breaking failure.

The failure process of aquifuge is well described with volumetric strain. Taking the later situation as an example. When the thickness is 1m, the developing process of volumetric strain is shown as Figure 8.

Figure 8. Volumetric strain cloud diagram of aquifuge.

As is indicated in Figure 8, since the maximum stress occurs at the edge of the tunnel face (4). Cracks tend to occur at the edge of tunnel face, when cracks intersect with each other, the total failure occurs.

5.3. Disaster mechanism
The effective stress variation curves at the bottom of the tunnel face (ID=0) and the center of the tunnel face (ID=1) are shown in Figure 9.

Figure 9. Curve of effective stress in different positions of tunnel face.
Comparing the difference of the effective stress between the central and the bottom of the tunnel face, it is found that when the aquifuge with different thickness is destroyed, similar characteristics are concluded. That is, the effective stress of the rock mass at the bottom edge of the tunnel face increases rapidly, and the failure occurs to form a water/mud inrush passageway, which is consistent with the actual situation of the project. When the thickness is smaller, the effective stress at the central of the tunnel face and the bottom increases synchronously, and the damage occurs almost at the same time.

6. Conclusion

The water inrush accident in Yingpanshan No.1 inclined shaft is caused by the nearby F2 water-bearing fault, and the minimum safe thickness based on elastic thin plate theory is reasonable. The rock mass larger than 10m should be retained during construction to ensure that the water barrier can be strengthened, the disaster-causing object can be eliminated and the construction safety be ensured.

Once the aquifuge thickness is smaller than the minimum safety thickness, water/mud inrush will occur on the tunnel face. The rock mass at the bottom of the tunnel face is destroyed at first, forming a water gushing channel.

when the thickness of the aquifuge is large, the overall extrusion failure mainly occurs; when the thickness of the waterproof wall is small, the middle fracture occurs, and the failure process of the tunnel face develops rapidly and the influence range is large.

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