Mechanical characteristics of karst tunnel lining structure under the action of groundwater from rainfall seepage

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Abstract. Heavy rainfall in areas with developed karst depressions will cause the water pressure behind the tunnel lining structure to rise rapidly, which brings about high safety risk of the lining structure. In order to determine the stress characteristics of the karst tunnel lining structure under the effect of rainfall seepage, a load-structure numerical model was established to analyze the changes in axial force, bending moment and safety factor under different water load conditions. The calculation results show that the single-point (small range) water pressure often leads to the damage of the arch and invert of the lining structure. When the pressure-bearing range increases, the damage of the foot and side wall of the lining structure tends to occur. When the overall range of the invert is subjected to water pressure, the damage of the lining structure from the invert to the side wall is likely to occur. Among them, the increasing pressure-bearing range is the most unfavorable water load state, and the safety factor of each part of the lining structure is significantly smaller than that in other three water load states. The research results can provide reference for the design of the lining structure section in similar conditions.

1. Introduction

In order to protect the underground water resources and environment around the tunnel, the water-proof and drainage design of mountain tunnel is mainly to stop water ingress combined with proper drainage, which put forward new challenges for the design of the tunnel lining structure [1]. When karst fissures are developed and the surface connectivity is good in the tunnel site area, especially when there is a clear hydraulic connection between the hidden caverns, karst troughs or underground rivers and the surface, groundwater tends to accumulate behind the tunnel lining after heavy rains, and thus the external water pressure of the lining would increase significantly [2-3]. In terms of range and value, the water pressure develops from local increase to range expansion and then to local decrease. The evenly distributed local water pressure on the lining increases the bending moment of the lining, reduces the axial force and increases the eccentricity, making the structure more unfavorable to force [4]. Under extreme water pressure, the secondary lining may crack [5]. Therefore, in order to understand the mechanical characteristics of the karst tunnel lining structure after rainfall, numerical calculation...
methods were used to analyze the changes in the force and safety factor of the tunnel lining structure under different water load conditions in this paper.

2. Modelling

2.1. Calculation model
The load-structure model was used for calculation where the lining structure was simulated with beam unit. The elastic model was employed as the constitutive model. The unit size was 0.5m. The interaction between the surrounding rock and the secondary lining was simulated by the normal phase spring element only under compression, with a total of 70 nodes and 70 units. The unit number and grid is shown in Figure 1.

![Fig 1. The unit number and grid of the model.](image)

2.2. Calculation parameters
According to the "Code for Design of Highway Tunnels" (JTG 3370.1-2018), the normal spring element which simulates the interaction between the supporting structure and the surrounding rock in the calculation model had an elastic resistance coefficient $k=150\text{MPa/m}$; the steel and concrete of the secondary lining were treated as a whole in accordance with equal elasticity Modulus principle. The elastic modulus of the secondary lining structure was 31.5GPa, gravity $\gamma$ was 25 kN/m$^3$, and Poisson's ratio was 0.2.

2.3. Load conditions
According to the change law of the water pressure on the lining structure of the karst tunnel after rainfall, four types of water load conditions (hereinafter referred to as state 1-4) were analyzed, including the initial show of water pressure on the lining structure, the multiple-point show of water pressures on the lining structure, the expanded range of water pressure on the lining structure, and the overall pressure-bearing state of the lining structure. The specific description of each load condition is as follows:

2.3.1. The initial show of water pressure on the lining structure (state 1). In state 1, a total of 6 working conditions are studied. The action range of water pressure is 1 linear meter (hereinafter referred to as 1m) and the water pressure is 100kPa. The working conditions 1 to 5 are the water pressure acting on the key parts of the secondary lining (position Numbered ① to ⑤): the arch, right hance, right hance, right side wall, right wall foot and inverted arch. Working condition 6 is that water pressure acts on all units from the arch to the invert (continuous change, range of water pressure is 1 linear meter * 37). The working conditions are shown in Figure 2.
2.3.2. The multiple-point show of water pressures on the lining structure (state 2). A total of 6 working conditions are calculated. The water pressure range is 1 linear meter and the water pressure is 100kPa. Working conditions 1 to 6 are water pressure acting on key parts of the lining structure (position numbers ①~⑥) including the arch, left hance, right hance, left side wall, right side wall, and inverted arch. The working conditions are shown in Figure 2.

![Fig 2. The working conditions in state 1 and state 2.](image-url)

2.3.3. The expanded range of water pressure on the lining structure (state 3). A total of 6 working conditions are calculated in this state. The water pressure is 100kPa. The range of water pressure is expanded from the arch to the right hance and to the side wall, and from the left hance to the left side wall. Finally the local water pressure acts on the middle of the invert. The calculation conditions are shown in Figure 3.

![Condition3-1](image-url)

![Condition3-2](image-url)
2.3.4. The overall pressure-bearing state of the lining structure (state 4). Given that the tunnel is located in the seasonal fluctuation zone, three situations are analyzed: (1) The arch and side wall of the tunnel are in the aquifer below the phreatic surface, and the invert is in the partial water-proof layer; (2) the arch and side wall are above the phreatic surface, but the invert is below the phreatic surface; (3) the entire tunnel is in the aquifer below the phreatic surface. The calculation conditions are shown in Figure 4.

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Fig 3. (a) (b) (c) The working condition in state 3.
3. Results and discussions

3.1. The mechanical characteristics of lining structure in state 1
Figure 5 shows the calculated bending moment and axial force cloud diagram of the lining structure under the condition 1-1 to 1-5.
Fig 5. The calculated bending moment and axial force cloud diagram.
The calculation results of the internal force and safety factor of the most unsafe part of the secondary lining under the condition 1-1 to 1-5 are shown in Table 1.

### Table 1. The internal force and safety factor of the most unsafe part of the secondary lining.

| Condition | Element no. | Part           | Bending moment (kN·m) | Axial force (kN) | Stress state       | Safety factor |
|-----------|-------------|----------------|-----------------------|------------------|--------------------|---------------|
| 1-1       | 1           | arch           | 59.7                  | -71.5            | large eccentricity | 13.3          |
| 1-2       | 60          | hance          | 60.5                  | -71.7            | large eccentricity | 13.1          |
| 1-3       | 52          | Side wall      | 49.5                  | -59.1            | large eccentricity | 16.0          |
| 1-4       | 48          | Foot of the wall | 26.7                  | -49.0            | large eccentricity | 30.1          |
| 1-5       | 36          | Middle of the invert | 90.5                  | -97.2            | large eccentricity | 8.7           |

It can be seen from Figure 5 and Table 1 that compared with the adjacent area without water pressure, the stressed secondary lining structure has the largest bending moment, the smallest axial force, and the smallest structural safety factor, which indicate that the lining structure is in an unfavorable stress state. For example, when water pressure acts on the hance (unit number 59, 60), the bending moment, axial force and safety factor (unit number 60) are 60.5 kN·m, 71.7 kN, and 13.1 respectively. The bending moment, axial force and safety factor of the area free of water pressure (unit number 62) are 27.9 kN·m, 78.8kN, and 30.2 respectively, and those of unit number 57 are 11.2 kN·m, 78.6kN, 87.5, respectively.

In order to more accurately describe the impact of changes in the position of water pressure on the safety of the lining structure, the safety factor distribution curve of the most unsafe part of the lining structure under Condition 1-6 is drawn in Figure 6.

![Fig 6. The safety of the lining structure under Condition 1-6.](image)

It can be seen from Figure 6 that the safety factor of the arch (0-7m) and most range of invert (14-17m) under water pressure changes little, while that of the side wall (7-10m) and a small part of the invert (12-13m) significantly increases by the influence of the transition circle (10-12m). The safety factor of the arch (0-7m) is 12.8-13.3, and the safety factor of the invert (14-17m) is 8.8-11.0. The reason is that the bending moment and axial force of the lining structure are greatly affected by the curvature of the member. The curvature of the transition circle is the largest, followed by that of the arch and the invert in sequence.

#### 3.2. The mechanical characteristics of lining structure in state 2

Due to space limitations, the bending moment and axial force cloud diagrams of the lining structure in Condition 2-1 to Condition 2-6 are not listed in detail, and only the safety factor of the key parts of the lining structure in Condition 2-1- Condition 2-6 are listed in Table 2.
Table 2. The safety factor of the key parts of the lining structure.

| Part          | Element no. | Condition 2-1 | Condition 2-2 | Condition 2-3 | Condition 2-4 | Condition 2-5 | Condition 2-6 | Condition 1 |
|---------------|-------------|---------------|---------------|---------------|---------------|---------------|---------------|-------------|
| arch          | 1           | 13.3          | 21.6          | 29.9          | 34.1          | 34.1          | 33.0          | 13.3        |
| Right hance   | 60          | 91.8          | 20.8          | 21.7          | 21.8          | 25.8          | 27.3          | 16.0        |
| Right side wall| 52          | 133.4         | 74.0          | 38.5          | 37.4          | 39.5          | 36.8          | 30.1        |
| Left hance    | 11          | 64.4          | 100.5         | 112.8         | 35.9          | 45.6          | 47.7          | 16.0        |
| Left side wall| 19          | 126.7         | 103.0         | 92.1          | 89.0          | 51.3          | 49.6          | 30.1        |
| Center of the invert | 36 | 175.2         | 133.4         | 116.8         | 117.1         | 107.8         | 10.6          | 8.7         |

It can be seen from the calculation results and Table 2 that: (1) the bending moment at the parts of secondary lining which bears the water pressure is obviously larger than that of the adjacent area which is free of water pressure. This is basically the same as when the water pressure starts to act on the lining structure; (2) the axial force at the position of the secondary lining which bears the water pressure is significantly smaller than that of the parts without water pressure. The axial force increases continuously with the increase of the number of pressure-bearing points (Condition 2-1 develops to Condition 2-6). The axial force of the arch increases from 71.5kN to 127.3kN, that of the right and left hance increase from 83.8kN to 126.7kN, that of the right and left side walls increases from 81.1kN to 127.4kN, and that of the invert is 79.1kN increases to 139.6kN; (3) compared with Condition 1, as the number of pressure-bearing points increases (Condition 2-1 develops to Condition 2-6), the safety factor of each key part of the secondary lining increases, and the safety of the secondary lining is improved. The safety factor of the arch, the right and left hance, the left and right side walls is increased from 13.3 to 33.0, from 16.0 to 27.3 and 47.7, and from 30.1 to 36.8 and 49.6 respectively.

3.3. The mechanical characteristics of lining structure in state 3

Due to space limitations, the bending moment and axial force cloud diagrams of the lining structure in the Condition 3-1 to Condition 3-6 are not listed in detail. The stress conditions and safety factors of the most unsafe parts and key parts of the lining structure are mainly listed. Specifically, the internal force and safety factor of the most unsafe parts of the lining structure in Condition 3-1 - Condition 3-6 are shown in Table 3.

Table 3. The internal force and safety factor of the most unsafe parts of the lining structure.

| Condition | Element no. | Part             | Bending moment (kN·m) | Axial force (kN) | Stress state       | Safety factor |
|-----------|-------------|------------------|-----------------------|------------------|--------------------|---------------|
| 3-1       | 1           | arch             | 59.7                  | -71.5            | large eccentricity | 13.3          |
| 3-2       | 65          | arch             | 110.5                 | -417.9           | large eccentricity | 8.1           |
| 3-3       | 48          | Foot of the wall | -130.0                | -571.1           | large eccentricity | 7.1           |
| 3-4       | 48          | Foot of the wall | -129.4                | -571.3           | large eccentricity | 7.2           |
| 3-5       | 48          | Foot of the wall | -126.0                | -574.1           | large eccentricity | 7.4           |
| 3-6       | 48          | Foot of the wall | -125.9                | -574.7           | large eccentricity | 7.4           |

It can be seen from the calculation results and Table 3: (1) Compared with Condition 2, with the further expansion of the stressed range (from arch to hance and to side wall), the bending moment of the lining does not change obviously while the axial force increases significantly. For example, the maximum axial force in Condition 3-6 is -558.0kN while that in Condition 2 is -139.6kN; (2) with the further expansion of the stressed range (from arch to hance and to side wall), the most unsafe position has changed. Besides, the minimum safety factor of the lining is reduced from 8.8 to 7.1. In detail, when the water pressure acts on the arch to the right hance (Condition 3-2), the part with the minimum safety
factor is at the center of the arch to the right hance. However, when the water pressure acts on the arch to the right side wall (Condition 3-3), the minimum safety factor appears at the foot of the wall. For Condition 3-1 to Condition 3-6, the calculated safety factor of the key parts of the lining structure are shown in Table 4.

| Part            | Element no. | Condition3 | Condition1 |
|-----------------|-------------|------------|------------|
| arch            | 1           | 13.3       | 29.9       | 15.2       | 15.6       | 15.6       | 13.3       |
| Right hance     | 60          | 91.8       | 32.1       | 14.3       | 14.3       | 14.7       | 14.7       | 16.0       |
| Right side wall | 52          | 133.4      | 27.9       | 15.7       | 15.8       | 16.2       | 16.3       | 30.1       |
| Left hance      | 11          | 64.4       | 30.8       | 23.4       | 19.8       | 25.5       | 25.4       | 16.0       |
| Left side wall  | 19          | 126.7      | 25.2       | 21.7       | 22.8       | 18.9       | 18.8       | 30.1       |
| Center of the invert | 36     | 175.2      | 32.7       | 27.1       | 27.1       | 26.8       | 18.3       | 8.7        |

As can be seen from Table 4, (1) when the water pressure acts on the parts (Condition 3-2, Condition 3-3) from the right arch to the hance to the side wall, the axial force in the other areas free of water pressure increases and the safety factor decreases. For example, in Condition 3-2, the safety factor of the left arch is reduced from 64.4 to 30.8 that of the left wall is reduced from 126.7 to 25.2, and that of invert is reduced from 175.2 to 32.7; in Condition 3-3, the safety factor of the left arch is further reduced from 30.8 to 23.4. The safety factor of the left wall 25.2 is further reduced to 21.7, and that of the inverted arch is further reduced from 32.7 to 27.1; (2) compared with Condition 1, the safety factor of the side wall of the lining structure in Condition 3-1 to Condition 3-6 is significantly reduced, and the safety factor of the key parts of the arch area (arch, hance) does not change much. It shows that in this state, the side wall is more easily damaged.

3.4. The mechanical characteristics of lining structure in state 4

Due to space limitations, the bending moment and axial force cloud diagrams of the lining structure under Condition 4-1 to Condition 4-3 are not listed in detail, and the stress conditions and safety factors of the most unsafe parts and key parts of the lining structure are mainly listed. Among them, the calculation results of the internal force and safety factor of the most unsafe part of the lining structure in Condition 4-1~Condition 4-3 are shown in Table 5.

| Condition | Element no. | Part            | Bending moment /(kN·m) | Axial force /kN | Stress state       | Safety factor |
|-----------|-------------|-----------------|------------------------|-----------------|--------------------|---------------|
| 4-1       | 48          | Foot of the wall | -108.1                 | -624.0          | large eccentricity | 9.0           |
| 4-2       | 47          | Foot of the wall | -364.8                 | -845.9          | large eccentricity | 2.3           |
| 4-3       | 47          | Foot of the wall | -342.3                 | -886.1          | large eccentricity | 2.4           |

It can be seen from the calculation results and Table 5: (1) When the invert of the lining structure is subjected to water pressure (Condition 4-2), the bending moment and axial force of each key part are greatly increased compared with that in Condition 4-1 (when the arch is under water pressure). However, compared with those in Condition 4-3 (when the whole lining structure withstands the water pressure), the bending moment and axial force of each key part has no significant change. For example, the bending moment of each key part in Condition 4-1 is -2.3 to 6.2 kN·m and the axial force is 584.2 to 595.8kN, the bending moment is 4.4 to 271.5 kN·m, and the axial force is 713.6 to 776.3kN in Condition 4-2. In Condition 4-3, the bending moment is -1.6 to 244.8kN·m, and the axial force is 750.1 to 827.4kN; (2)
In the Condition 4-1 to Condition4-3, the foot of the wall is the most unsafe part. Especially, the safety factor of the foot of the wall is greatly reduced in Condition 4-2 and Condition 4-3, indicating that structure damage is very likely to occur.

The calculation results of the safety factor of the key parts of the lining structure in Condition 4-2 and Condition 4-3 are shown in Table 6.

| Part             | Element no. | Condition4-1 | Condition4-2 | Condition4-3 | Condition1 |
|------------------|-------------|--------------|--------------|--------------|------------|
| arch             | 1           | 22.8         | 18.4         | 18.3         | 13.3       |
| Right hance      | 60          | 23.2         | 18.3         | 18.4         | 16.0       |
| Right side wall  | 52          | 21.8         | 15.5         | 13.0         | 30.1       |
| Left hance       | 11          | 23.3         | 18.6         | 18.1         | 16.0       |
| Left side wall   | 19          | 22.0         | 13.6         | 12.2         | 30.1       |
| Center of the invert | 36      | 23.6         | 3.1          | 3.6          | 8.7        |

It can be seen from Table 6 that: (1) Compared with that in Condition 4-1, the safety factor of each key part in Condition 4-2 is greatly reduced, and compared with Condition 4-3, the safety factor of each key part has little change. For example, the safety factor of each key part is 21.8 to 23.6 in Condition4-1, 3.1 to 18.6 in Condition 2, and 3.6 to 18.4 in Condition 3; (2) Compared with that in Condition 1, the safety factor of the key parts of the lining structure (arch, hance) is increased in Condition 4-1 to Condition 4-3. The safety factor of the side wall and inverted arch is reduced and they are generally smaller than that of the key parts of the arch, indicating that it is more likely to cause the damage in the invert and the side wall.

4. Conclusions

Based on the numerical calculation of the force condition of the lining structure under various water loading conditions, the following main conclusions can be drawn after comprehensive analysis:

(1) When the lining structure is subjected to a single point action of local water pressure, the safety factor of pressure-bearing part is the smallest. When the local water pressure is applied to the invert range or the arch area, the minimum safety factor of the lining structure has little difference. However, it is more unfavorable when it acts on the side wall and the transition circle range, which makes the structure more prone to damage in the arch and the invert under the water pressure.

(2) When the local water pressure acts on an increased number of positions which have a certain distance between each other, the bending moment, axial force and safety factor of the lining structure at the position subjected to the water pressure are still extreme points. The lining structure is safer than when the local water pressure acts on a single point. The damage of the lining structure generally does not occur in this state.

(3) The expansion of the range subjected to water pressure will reduce the safety of the lining structure, and the force condition of the lining structure that is not affected by the hydraulic pressure has also changed significantly. Compared with the single point pressure-bearing state, the safety factor of the arch is not much different. In this state, the foot of the wall and the side wall are major damage parts.

(4) In the state that the overall lining structure is subject to water pressure, the invert range is in relatively unfavorable condition. Compared with the state that the pressure-bearing range is expanded, the safety of the lining structure in the arch range is relatively high. The damage mainly occurs in the range from the invert to side wall in this state.

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