Analysis on the influence of water pressure on the safety of karst tunnel lining structure

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Abstract. Tunnel lining structure in water-rich karst area bears random high water pressure, which seriously threatens the safety of lining structure. In order to determine the influence of water pressure on the safety of lining structure of karst tunnel, a numerical model of load-structure was established, and the safety factors of lining structure under different circumferential and longitudinal action ranges of water pressure were compared and analyzed. The calculation results show that the safety factor of arch and side wall of lining structure is the lowest when the circumferential action ranges of water pressure are 0.3S and S (S refers to the distance from vault to the maximum span). The safety reduction factor of lining structure is 0.4-1.0 when the longitudinal action range of water pressure is 4m-36m. The research results can provide a basis for designing lining structure of tunnels in water-rich karst stratum.

Keywords: Karst tunnel; safety; numerical analysis; lining structure; high water pressure.

1. Introduction

In the water-rich karst stratum, the tunnel lining structure bears high water pressure. Because of the randomness of karst development, it is difficult to determine the position of karst water action in the tunnel lining. In a certain longitudinal length range, it is possible to distribute in the vault, spandrel, vault, side wall, arch foot and invert, etc. Different water pressure action positions and concentration area affect the lining structure safety to different degrees [1–3]. The design of tunnel lining structure in such stratum needs to consider the effect of local water pressure, but there is no consensus on the load mode, which causes many safety problems of tunnel lining structure [4–5]. Therefore, the load-structure model was established by numerical calculation method in this paper. By comparing the safety factors of lining structure in different circumferential and longitudinal action ranges of water...
pressure, the paper analyzed the influence of water pressure on the lining structure safety of karst tunnel, and provided references for the design of tunnel lining structure in water-rich karst stratum.

2. Influence of circumferential action range of water pressure

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.

2.2. Calculation factor
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
There are eight water pressure conditions (Condition 1-1 - Condition 1-8). The water pressure is 100 kPa. The action range of water pressure is enlarged successively from the vault to the right arch vault, the maximum span on the right side, the right wall foot, the middle of the invert, the left wall foot, the maximum span on the left side, the left arch vault, and finally the whole ring, which is a typical development process of water pressure. The calculated conditions are shown in Figure 2.
2.4. Analysis of calculation results

The distribution of lining structure safety factor of working condition 1-8 is shown in Figure 3.

![Schematic diagram of load conditions](image)

**Figure 2** Schematic diagram of load conditions

As can be seen from the figure 3:

(1) The "low" safety factors of condition 1 concentrate in the range of #1-#18, and the safety factors in #18-#37 increase obviously. The distribution law of safety factor of condition 2-3 is
basically the same. The "low" safety factors concentrate in the range of #19-#29, and the "medium" safety factors in #1-#19 while the "high" safety factors in #29-#37; of condition 4, the "low" safety factors concentrate in the range of #21-#37, and the "high" safety factors in #1-#21.

(2) The distribution law of safety factor of condition 5-8 is basically the same. The "low" safety factors concentrate in the range of #22-#37 (the range of transition circle and invert), and the "high" safety factors in #1-#22. Considering the back pressure effect (about 1.5m thick) of invert filling and pavement structure, the safety fault of lining structure in this range can be ignored.

(3) In the range of #0-#18, the safety factor of condition 1 is obviously smaller, in which the factor of condition 2 in #10-#14 is small, but it is greater than that of condition 1 in #3-#10. Therefore, the load state of condition 1 should be used for checking the safety of lining structure in this range.

(4) In the range of #18-#20, the safety factor of condition 7 is smaller than that of condition 2, but in #21-#22, the safety factor of condition 2 is smaller than that of condition 7, and the safety factors in #21-#22 are smaller than that in #18-#20, so the safety of #18-#22 (side wall) should be checked by condition 2.

In conclusion, the calculation results of the minimum safety factors of arch and side wall under condition 1 and 2 are 8.1 and 11 respectively. However, considering the diversification of tunnel lining structure forms (curvature, multi-center circle) and other factors, the load state of condition 1 and 2 should be comprehensively used to check the safety of karst tunnel lining structure.

For condition 1, it is necessary to further analyze the influence of load area change on arch safety factor to determine the most reasonable load state of condition 1. Therefore, taking the action range of water pressure as the variable (expanding clockwise, and water pressure is 100kPa), the influence of the change of water pressure action range on the safety factor of each component is analyzed. The calculated conditions are shown in Figure 4.

![Figure 4 Schematic diagram of load condition](image-url)

From the calculation results, it can be seen that the "low" safety factors of each working condition mainly concentrate in the range of #1-#18. In order to highlight the key point, only the safety factors in #1-#18 are given. The distribution of lining structure safety factors under each working condition is shown in Figure 5.
It can be seen from Figure 5 that the distribution law of safety factors in the arch range of lining structure under each working condition is the same. There are two low-lying areas in the distribution of the safety factor of the arch, which are the positive bending moment area within the load action range and the negative bending moment area outside the range. The safety factor of the lining structure within the load action range is relatively small, and thus the safety of the arch should depend on this range. The location and value of the minimum safety factor within the load action range are shown in Table 1.

Table 1 Safety factors of key positions of lining structure

| Condition | Element no. | Bending moment /(kN·m) | Axial force (kN) | Stress state         | Safety factor |
|-----------|-------------|-------------------------|------------------|----------------------|---------------|
| 2-1       | 64          | 97.7                    | -459.8           | large eccentricity   | 9.6           |
| 2-2       | 65          | 104.6                   | -440.6           | large eccentricity   | 8.8           |
| 2-3       | 65          | 110.5                   | -417.9           | large eccentricity   | 8.1           |
| 2-4       | 66          | 116.7                   | -394.9           | large eccentricity   | 7.5           |
| 2-5       | 66          | 120.1                   | -369.5           | large eccentricity   | 7.1           |
| 2-6       | 67          | 125.2                   | -341.3           | large eccentricity   | 6.7           |
| 2-7       | 67          | 125.2                   | -312.3           | large eccentricity   | 6.6           |
| 2-8       | 68          | 126.6                   | -281.7           | large eccentricity   | 6.5           |
| 2-9       | 68          | 122.6                   | -248.0           | large eccentricity   | 6.6           |
| 2-10      | 69          | 118.9                   | -215.2           | large eccentricity   | 6.8           |
It can be seen from Figure 5 and Table 1 that the safety factor of lining structure arch is the smallest, which is 6.5, when the water pressure action range is 4m; when the water pressure action range is 3-4m, the safety factor increases with the decrease of the water pressure action range, which is 6.5-6.8; when the water pressure action range is 4-7.5m, the safety factor increases with the increase of the water pressure action range, which is 6.5-9.6.

3. Influence of longitudinal action range of water pressure

By establishing a three-dimensional load-structure model, the variation law of safety factor of lining structure with the change of longitudinal action range of water pressure is analyzed. The calculation model adopts load-structure model, and the lining structure is simulated by plate element. The constitution is elastic model, the element circumferential size is 0.5m, the longitudinal size is 1.0m; the normal phase spring element only under compression is used for simulating between the primary support and the secondary lining, and there are 70×36 nodes, 70×36 elements, while the longitudinal length of the model is 36m. The longitudinal boundary of the model constrains the longitudinal horizontal displacement and rotational degrees of freedom, and the calculation parameters are the same as those in Section 2.2. The circumferential action range of water pressure is 4m, and the longitudinal range is variable. The calculation scheme is shown in Table 2 and the element grid is shown in Figure 6.

| Lining section | Water pressure /kPa | Longitudinal length of water pressure /m |
|----------------|---------------------|---------------------------------------|
| 4a             | 20                  | 2, 4, 6, ……14, 36                     |
|                | 40                  |                                       |
|                | 80                  |                                       |
| 5a             | 200                 |                                       |
|                | 500                 |                                       |
|                | 800                 |                                       |

Figure 6 Model element

The variation of structural safety factor of 4a lining section and water pressure ratio $Z_{w,n}$ with the longitudinal range of water pressure under the water pressure of 20kPa, 40kPa and 80kPa is shown in Figure 7, in which $Z_{w,n}$ is the change in lining structure safety factor with different proportions of the...
compressed longitudinal length to the total longitudinal length (36m). \( Z_{w,n} = \frac{(k_2-k_n)}{(k_2-k_{36})} \), where \( k_n \) (\( n = 2, 4, 6...14, 36 \)) denotes the safety factor of lining structure at each longitudinal length, and \( W=20, 40, 80 \text{kPa} \) in \( Z_{w,n} \).

As can be seen from Figure 7:

1. The safety factor of lining structure decreases with the increase of longitudinal length, and the decreasing range becomes smaller gradually. For example, when the longitudinal length under 80kPa is 2m-4m, it decreases by 0.6 and when the longitudinal length is 12-14m, it decreases by 0.1; when the longitudinal length under 40kPa is 2m-4m, it decreases by 0.5 and when the longitudinal length is 12-14m, it decreases by 0.1; when the longitudinal length under 20kPa is 2m-4m, it decreases by 0.3 and when the longitudinal length is 12-14m, it decreases by 0.1.

2. The larger the water pressure is, the larger the proportion \( Z \) is. With the increase of the longitudinal length, water pressure proportion \( Z \) increases gradually, and there is little difference between water pressure proportion \( Z \) under 20kPa and 80kPa. For example, \( Z_{80,4}-Z_{20,4}=18.0, Z_{80,14}-Z_{20,14}=9.3 \) show that the sensitivity of water pressure (low water pressure (20kPa) and high water pressure (80kPa)) to the influence of longitudinal length change on the safety factor of lining structure is low. When analyzing the influence of longitudinal length change on the safety factor of lining structure, it can be characterized by the mean value of high water pressure and low water pressure.

Under water pressure of 200kPa, 500kPa and 800kPa, the variation of safety factor of 5a lining section and water pressure proportion \( Z_{w,n} \) with the longitudinal range change of water pressure action is shown in Figure 8.
Figure 8 Variation law of safety factor of 5a lining section

As can be seen from Figure 8:

1) The safety factor of lining structure decreases with the increase of longitudinal length, and the decreasing range of 500kPa and 800kPa curves gradually decrease and that of 200kPa curve first increases (longitudinal length < 10m) and then decreases (10m-36m). For example, when the longitudinal length under 800kpa is 2m-4m, it decreases by 0.9 and when it is 12-14m, it decreases by 0.07; when the longitudinal length under 500kPa is 2m-4m, it decreases by 1.2 and when it is 12-14m, it decreases by 0.1; when the longitudinal length under 200kPa is 2m-4m, it decreases by 0.3 and when it is 12-14m, it decreases by 0.1.

2) The larger the water pressure is, the larger the proportion Z is. Water pressure proportion Z increases with the increase of longitudinal length. There is little difference between water pressure proportion Z under 500kPa and 800kPa, while the value of Z under 200kPa is obviously smaller than that under 500kPa and 800kPa.

4. Conclusions
Based on the numerical calculation of lining structure safety under various water pressures, the main conclusions are as follows:

1) The safety factors of two circumferential distribution forms of water pressure are the smallest: one form is when water pressure action range $S_1=4m$, the other is when the distance from vault to the maximum span $S_2=13.8m$. At the same time, considering the diversity of tunnel lining structure forms (curvature and multi-center circle), the action range of water pressure should take the distance from vault to the maximum span as the reference standard and take the relative quantity. Water pressure action range $S_1 = 4/13.8 S \approx 0.3 S$.

2) When the plane strain load - structure method is used to design and analyze the lining structure, the water pressure proportion calculated based on the calculated safety factor of the lining structure should be taken as the reduction factor according to the actual situation of engineering geology. The reduction factor corresponding to the longitudinal action range of 4m-36m is 0.4-1.0.

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