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Water pressure and stress characteristics of lining structure in water rich karst tunnel

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Water pressure and stress characteristics of lining structure in water rich karst tunnel

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Abstract. As more and more karst tunnels have been operated, the disease of operating karst tunnels becomes more and more serious. In order to analyze the distribution regularities of water pressure of lining structure under the influence of rainstorm, a three-dimensional numerical model was established to study the distribution pattern of water pressure of lining structure in water-rich karst tunnel, and the internal force of lining and the applicability of half-pack and half-drain in water-rich karst tunnels were also analyzed. The results show that the water pressure in the vault of the tunnel is small, and is high in the invert area. The invert is subjected to tensile stress. For water-rich karst tunnels, the invert of the tunnel bears relatively large water pressure when the half-pack and half-drain are adopted, which is of poor applicability, so the center of the invert is easy to crack. Therefore, it is necessary to optimize the waterproof and drainage modes. The results can provide a reference for the design of water-rich karst tunnels.

1. Introduction

China is the country which has the most extensive karst distribution, with karst phenomena in many provinces, municipalities and autonomous regions. As more and more karst tunnels have been built, there are frequent karst diseases happened in operated tunnels, such as the serious leakage accident of Jianshanying tunnel. The damage of tunnel invert in the Xiaogaoshan tunnel, due to the sudden rainstorm. The side wall cracking of the Dazhulin tunnel on the Zhu-Six Line. According to the research on the diseases of karst tunnels, the sudden water pressure caused by rainfall and other factors is the main factor leading to the diseases of operating karst tunnels [1-3]. At present, most karst tunnels in China adopt half-pack and half-drain waterproof and drainage mode. Is this kind of waterproof and drainage mode suitable for karst tunnels with sufficient rainfall recharge? What is the distribution regularity of water pressure of lining structure under the influence of heavy rain? These are all problems that need to be solved.

The external water pressure of karst tunnel lining has been studied by many scholars at home and abroad. Zhang Peng [4] studied the distribution regularity, stress field and seepage field of the grouting ring and the water load of the lining of the tunnel by using model test method, based on Xiamen Xiang 'An undersea tunnel. Wang Sen [5] made an in-depth study of the water pressure and structural stress characteristics of the lining of water-rich karst tunnels based on Zhongliangshan tunnel. Zhang Mingde

[6] taking the karst tunnel of Yiwan Railway as the engineering background, studied the seepage field distribution regularity of the lining structure and the influence of grouting control factors and stress characteristics under the combined action of seepage field, stress field and seepage field through theoretical analysis, numerical simulation and model test. Some relevant scholars also studied the water pressure distribution regularities of karst tunnels [7,8]. In the analysis of the above research, most of them simplify the drainage system of tunnels and generally adopt two simplified methods: one is to simplify the three-dimensional space problem into a two-dimensional plane problem by using the theory of equivalent drainage area, and turn the drainage hole into a drainage gap with a certain width. The other is the establishment of three-dimensional seepage model, the waterproofing board of the tunnel, through a certain permeability coefficient reduction, considered in the tunnel secondary lining solid. However, the permeability coefficient and thickness of each material have a significant impact on the water pressure distribution of the lining. The simplified modeling method is bound to have a certain impact on the results. In addition, most of the current research pay more attention to the influence of karst tunnel grouting ring on the waterproof and drainage of tunnel, and neglect the applicability of half-pack and half-drain mode in water-rich karst tunnels.

Based on this, the three-dimensional numerical model was established in this paper. Considering the drainage situation in the tunnel, the waterproofing board, non-woven fabric, drainage pipes and central drainage ditch of the tunnel were simulated by solid units. The water pressure distribution regularity behind the lining was also analyzed by considering the influence of rainstorm. The research results can provide reference for the waterproof and drainage optimization design of karst tunnel.

2. Establishment of 3-D numerical model

2.1. Calculation model

In this calculation, a 3-D seepage model was established. The model was: 115m in length, 14m in width and 112m in height. Around the boundary from the center line of the tunnel was 57.5 m. The lower boundary from the bottom of the tunnel was 49.7 m. To border on the free surface, the deep of the tunnel was 49.7 m. The grade of the surrounding rock was V. The calculation model was shown in Figure 1. Considering the drainage situation in the tunnel, solid units were adopted for the waterproof board, non-woven fabric, drainage pipe and central drainage ditch of the tunnel. The waterproof board, non-woven fabric and drainage system of the tunnel were shown in Figure 2. The displacement boundary conditions of the model were as follows: the displacement constraints in the X direction were applied on both sides of the boundary, the displacement constraints in the Z direction were imposed on the bottom boundary, and the displacement constraints in the Y direction were imposed on the front and rear surfaces. The load only considering the action of gravity. The seepage boundary conditions were as follows:

(1) It is assumed that the top surface is a free underground water surface, and there is a large amount of rainfall supply. The underground water level does not decrease with the drainage in the tunnel.

(2) The left and right sides are stable boundaries, where the water head at each point is equal water head, H= h.

(3) The base is the impermeable boundary, where the normal flow velocity is 0 and the flow rate is 0.

(4) The front and back boundary of the model, where the water head at each point is equal water head, H= h.

(5) The central drainage ditch at the entrance and exit of the tunnel is set to be submerged and the pressure head is set to be 0.

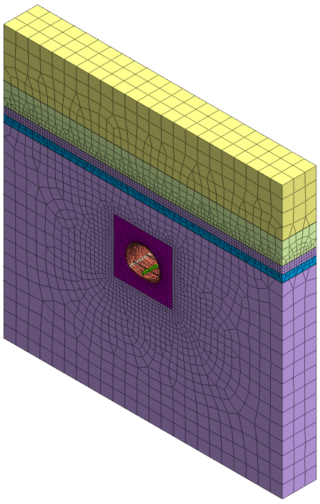


Figure 1. The calculation model

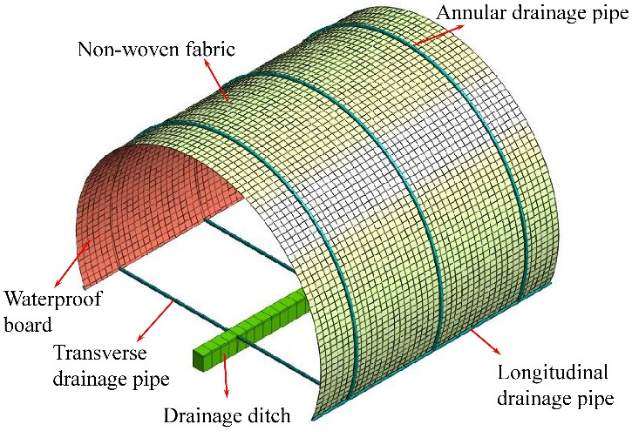


Figure 2. Tunnel waterproof and drainage system

The calculation processes is as follow:

a) firstly, it is assumed that the underground water level and rainfall supply layer are located at the surface; the water pressure behind the tunnel lining is calculated, the distribution regularity of water pressure is analyzed, and the water pressure is extracted to the load structure model, so as to conduct the safety check calculation for the lining structure; b) if the safety factor does not meet the requirements, lower the height of the underground water level and the rainfall supply layer, carry out the above calculation process again, and conduct the safety check calculation of the lining structure; c) repeating the above process until the lining structure meets the safety requirements, and then the critical water pressure and the internal force behind the lining are calculated.

2.2. Parameters of model

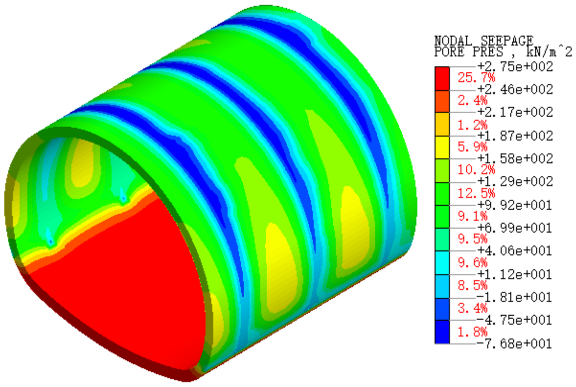
The radius of the tunnel is 7.2m, and the initial support adopts shotcrete C25, which is 29cm thick. The secondary lining is made of C35 reinforced concrete with 55cm arch wall and 65cm invert. The thickness of both waterproof board and non-woven fabric is 3mm, the diameter of drainage pipe is 10cm, and the size of central drainage ditch is: length × width = 84.4cm × 60cm. Only the water pressure behind tunnel lining is extracted in three-dimensional model. Therefore, the most important parameter are the permeability coefficient of materials, which are shown in Table 1 [9,10].

Table 1. Permeability coefficient of materials（cm/s）

Materials	Surrounding rock	Preliminary lining	Secondary linning	Waterproof board	Non-woven fabric	Drainage pipe
Permeability coefficient	2×10^{-4}	2×10^{-6}	2×10^{-8}	4×10^{-9}	8×10^{-4}	4

3. Water pressure distribution regularities behind the tunnel lining

In order to facilitate analysis, the height of water head above the tunnel secondary lining vault was taken as the reference, the water pressure behind the tunnel lining was calculated step by step, until the critical height of water head was found when the tunnel lining structure does not meet the safety requirements. When the height of water head of the tunnel vault was 19m, the water pressure distribution behind the tunnel lining was shown in Figure 3. The cross section in the middle of the two annular drainage pipes was taken as a typical section, and the water pressure of the lining considering the drainage and non-drainage of the tunnel was as shown in Figure 4.



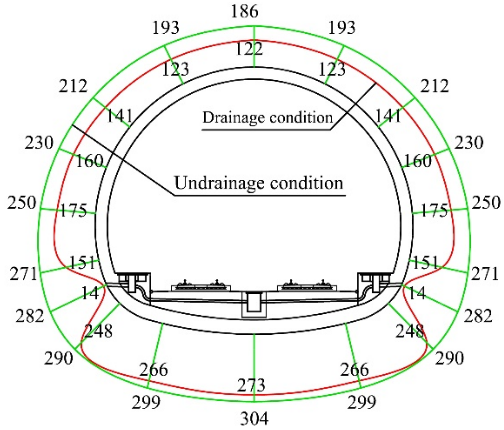


Figure 3. Distribution of water pressure (kPa) Figure 4. Envelope diagram of water pressure(kPa)

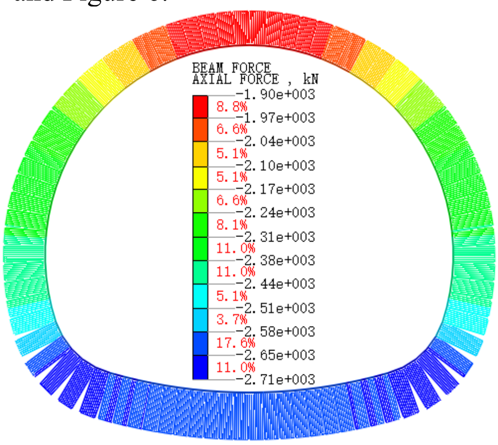
As can be seen from Figure 3 and Figure 4, in the case of considering tunnel drainage, the water pressure at the upper part of the tunnel is relatively small. At the location of annular drainage pipes and longitudinal drainage pipes, the water pressure is close to 0, while at the location of invert, the water pressure is relatively high, which is mainly related to the half-pack drainage way adopted by the tunnel.

When analysis from the perspective of water pressure reduction, the water pressure of tunnel vault reduced from 186 kPa to 122 kPa, water pressure reduction by 34%, while the water pressure of invert center reduced from 304 kPa to 273 kPa, water pressure reduction only by 10%, which shows that using half-pack drainage way, in the case of a large amount of rainfall supply, the waterproof and drainage system of the tunnel may not be able to timely discharge of karst water or surrounding rock crevice water, which causes a high water pressure on the invert of the tunnel.

In order to further analyze the influence of water pressure behind tunnel lining on the lining structure, a load structure model was established to apply water pressure as an external load to tunnel lining. At the same time, considering the action of surrounding rock pressure, the stress of lining structure was analyzed.

4. The internal force of lining structure

Considering tunnel drainage, the axial force and bending moment of lining were respectively shown in Figure 5 and Figure 6.



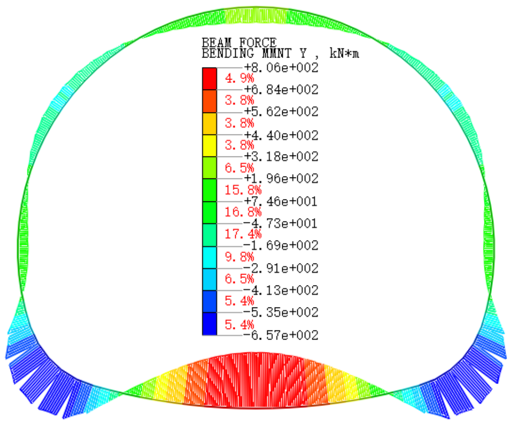


Figure 5. The axial force of lining (kN) Figure 6. The bending moment of lining (kN.m)

According to Figure 5 and Figure 6, when the height of total water head of the vault is 19m, the water pressure in the arch wall is greatly reduced due to the drainage of the tunnel. The axial force of the invert of the tunnel lining and the intersection part of the side wall is larger, and the maximum axial force of the right-side wall is 2710kN, which is 1.4 times of the axial force of the vault. The bending moment is larger at the center of the invert. The maximum positive bending moment is 806kN.m. The invert bears flexural-tensile stress, which makes it easy to crack.

It can be seen from the above analysis that when the water-rich karst tunnel adopts the conventional half-pack and half-drain waterproof and drainage method, the water pressure in the arch wall of the tunnel is significantly reduced, but the invert is under greater water pressure. Therefore, for water-rich karst tunnels, the half-pack and half-drain waterproof and drainage way is poor in applicability and needs to be optimized.

5. Conclusions

(1) In the case of considering tunnel drainage, the water pressure at the upper part of the tunnel is relatively small. At the location of annular drainage pipes and longitudinal drainage pipes, the water pressure is close to 0, while at the location of invert, the water pressure is relatively high.

(2) When the height of total water head of the vault is 19m, the water pressure in the arch wall is greatly reduced due to the drainage of the tunnel. The axial force of the invert of the tunnel lining and the intersection part of the side wall is larger. The bending moment is larger at the center of the invert. The invert bears flexural-tensile stress, which makes it easy to crack.

(3) When the water-rich karst tunnel adopts the conventional half-pack and half-drain waterproof and drainage method, the water pressure in the arch wall of the tunnel is significantly reduced, but the invert is under greater water pressure. Therefore, for water-rich karst tunnels, the half-pack and half-drain waterproof and drainage way is poor in applicability and needs to be optimized.

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