Study of the mechanism of water inrush in karst tunnel based on transparent rock mass physical model test

Lijun Wang1, Peng Huang1, Luoyi Chen1, Jian Wang1, Zhilong Zheng1, Jianxin Ma1

1 PowerChina Chengdu Engineering Corporation Limited, Chengdu Sichuan 611130

E-mail(corresponding author): cky_wlj@163.com

Abstract. Water inrush is the main geological disaster occurred during karst tunnel excavation, which will cause huge economic losses and casualties. Therefore, it is important to investigate the water inrush mechanism of karst tunnel surrounding rock mass for preventing water inrush disasters in karst tunnel construction. Herein, Xinjie Tunnel of Kaili Ring Expressway in Guizhou Province is chosen as an object, where a large water-filled karst cave may locate on the upper right side of the tunnel cross section according to the geological survey report. Then taking the typical tunnel cross section as the prototype, a three-dimensional geomechanical model of Xinjie tunnel is made by using transparent rock mass material based on similarity theory, on which laboratory water inrush physical model tests are performed. Based on laboratory physical model test results, the mechanism of water inrush in karst tunnel is investigated, from which it indicates that the groundwater mainly flows through the fissures of the tunnel surrounding rock during water inrush process, and the water inflow rate mainly depends on the initial water pressure of the water-filled karst cave. When water pressure increases from 0.1MPa to 0.2MPa, the water inflow increases by 84.4%, but the increase rate of water inflow will slow down when water pressure further increases. Compared with the previous level of water pressure, the water inflow only increases by 7.2%. Hence, in the excavation of karst tunnel, it is necessary to seal the fractures by grouting timely and release the water pressure of the karst cave for preventing water inrush accident. The research results will provide important guiding significance for the excavation of karst tunnel.

1. Introduction

The karst is a kind of typical adverse geology body widely existed in Southwestern China, which includes underground rivers, karst caves, karst conduit, and corrosion fissures. During the implementation of the western development strategy, many highway or railway tunnels will be constructed in karst areas where geological disasters such as water and mud inrush occur frequently, which will pose serious threat to the safety of construction workers and cause huge economic losses. Therefore, it is of great importance to investigate the mechanism of water inrush in the karst tunnel construction. Li Li-ping et al[1] had studied the mechanism of water-rock interaction in karst tunnel by using theories of karst geology, engineering hydraulics and fracture mechanics and the effects of such mechanism on water outburst and projecting mud soil during the construction of karst tunnel had also been explored. Li Shucai et al[2] had analyzed the occurrence condition, criterion, safety thickness of different types of water inrushes and the development trend of water inrush mechanism. Huang Xin et al[3] proposed a prevention structure assessment method for rapidly assessing the safety of karst
tunnels based on an evaluation index system considering hydrodynamic condition, unfavorable geology, prevention thickness and surrounding rock characteristics, and this method was successfully applied in the Yesanguan railway karst tunnel. Liu Zhao-wei et al\cite{10} investigated the gradually-developed-process of karst water burst in Yuanliangshan tunnel by combination of field survey, numerical simulation and theoretical analysis.

In recent years, some theoretical and experimental researches on the water inrush mechanism in the karst tunnel have been reported by considering the case that a water-filled karst cave exists in front of the tunnel excavation working face. Hwang and Lu\cite{5} proposed a semi-analytical approach for analyzing the problems of the tunnel water inflow by using the classical ground water theory. Guo\cite{6-7} adopted elastic beam and plate theories to investigate the rock stratum between the tunnel and the surrounding karst cave, and established theoretical solutions of the minimum safety thickness based on rock strength criterions. Xu et al\cite{8} proposed a semi-analytical solution to determine the minimum safety thickness of the rock stratum for resisting water inrush from filling-type karst caves based on the slice method and elastic mechanics method. Wu et al\cite{9} developed generalized models and computational techniques for karst caves filled with water and water-mud mixture in front of the tunnel face to estimate the required thickness of supporting rock stratum in order to prevent water and mud inrush under earthquake action. Jiang\cite{10} established a simplified model for simulating the process of water inrush and obtained the minimum safety thickness of rock wall for the tunnel face. Meanwhile, Jiang\cite{10} choose Yue-long-men tunnel of Chengdu-Lanzhou Railway line as engineering background, and a series of large-scale geomechanical model tests were carried out based on a three-dimensional model test system. Liang et al\cite{11} performed physical simulation experiment of water inrush in tunnel excavation to analyze the change laws of stress, displacement and water pressure. Yang et al\cite{12} had conducted a model test of water inrush under fluid-solid coupling conditions and the mechanism of water catastrophe evolution was revealed by analyzing the changes of the stress, displacement, and water pressure in the test. However, most of recent researches on the water inrush mechanism focus on the condition that karst cave is located in front of the tunnel excavation face, little attention has paid to the conditions that karst cave is located in the side of the tunnel. Pan Dong-dong et al\cite{13} had developed a new type of model test system to conduct solid-fluid coupling model tests on lagging water-inrush of karst cave, and the variation of multi-field information such as displacement, stress and seepage pressure is effectively revealed. Li Lang et al\cite{14} also developed a three-dimensional model test system for simulation of waterinrush geohazards to study the minimum thickness of waterproof slab in long and deep karst tunnels. Taken the karst cave tunnel of Zhongdian Highway as an object, Tan Dai-ming et al\cite{15} studied the surrounding rock stability of karst cave beside the tunnel by using the finite difference software FLAC\textsuperscript{3D}, and the numerical calculation results were compared with field monitoring results. Chen Guo-qing et al\cite{16} took the Mingyueshan tunnel as an example and studied the mechanism of water burst in karst tunnel excavation by using numerical simulation method based on Darcy’s law, Brinkman equation and Navier-Stokes equations.

Furthermore, as the material used in existing physical model tests is opaque, the transport of water in the tunnel surrounding rock mass during water inrush process is invisible. In order to overcome the shortcomings of traditional model materials, a new transparent soil or rock mass technology has been developed and applied to investigate the deformation and failure behavior of the surrounding rock mass of tunnel by some rock mechanics researchers\cite{17-20}. As the physical model made by transparent soil or rock mass materials is transparent, its internal deformation and failure properties can be observed easily, which may provide a new way for investigating the whole water inrush process of karst tunnel in physical model test.

Hence, in this paper, taking a typical expressway karst tunnel constructed in Guizhou province of China as the project background, a transparent model material for simulating tunnel surrounding rock mass was firstly developed, then a laboratory three-dimensional geomechanical model of the karst tunnel was prepared to observe the water inflow during water inrush process, on the basis of which the water inrush mechanism of karst tunnel was investigated.
2. Project background

Xinjie Tunnel is located in the northern section of Kaili Ring Expressway, Guizhou Province, where karst is widely developed. According to the preliminary geological survey results, karst is the typical poor geology in Xinjie tunnel site, of which the main forms are karst cave, sinkhole and karst depression, as shown in figure 1.

![Figure 1. Three main forms of karst in Xinjie tunnel site. (a) karst cave, (b) sinkhole and (c) karst depression](image)

Especially, from the result of No.CZK3 drilling, it is found that a large karst cave with a height of about 22.1m is located on the right side of the right line of Xinjie tunnel, of which the geological profile is shown in figure 2. Although the karst cave is almost empty when drilling during preliminary geological survey, it may be filled with water during flood season, which may cause water inrush accident in tunnel excavation. In order to determine the maximum water pressure of the karst cave during flood season, the groundwater level in surrounding rock mass adjacent to the karst cave is obtained by on-site pumping tests, from the results of which the maximum water pressure of the karst cave is estimated by about 0.3MPa. Therefore, it is important and necessary to investigate the water inrush process and mechanism of this large water-filled karst cave and evaluate its effect on the safety of tunnel surrounding rock mass excavation. Herein, physical model test is applied for this research purpose.

![Figure 2. Geological profile of No.CZK3 drilling](image)

3. Physical model preparation and test setup

In order to investigate the water inrush mechanism of karst tunnel, physical model test is applied by taking the geological profile of No.CZK3 drilling of Xinjie tunnel as the prototype, and a novel kind of transparent rock mass is prepared as artificial surrounding rock mass material. Then a three-dimensional geomechanical model of Xinjie tunnel is made by use of this novel transparent rock mass material, on which the karst tunnel water inrush physical model tests are performed. In the following
section, the preparation of a three-dimensional geomechanical model and laboratory water inrush tests will be described in detail.

3.1. Transparent rock mass material

The transparent rock mass material was composed of dodecane, silicon powder and white mineral oil, where the mixture of dodecane and white mineral oil was chosen as a cementitious agent and silicon powder was chosen as an aggregate. Firstly, the dodecane and white mineral oil were mixed with a volume ratio of 1:1.6 to prepare the cementitious agent, then the silicon powder was poured into the cementitious agent and mixed with a mass ratio of 0.3:1. Finally, the mixture is processed by a vacuum pump to eliminate bubbles. The procedures of preparing transparent rock mass material were shown in figure 3.

![Figure 3](image)

Figure 3. Procedures of preparing transparent rock mass material. (a) silicon powder, (b) mixing the aggregate and cementitious agent, (c) vacuum processing and (d) transparent rock mass material

3.2. Three-dimensional geomechanical model preparation

According to the typical cross-section dimensions of Xinjie tunnel and the size of karst cave, the geometric similarity ratio of physical model test was chosen as 225, thus the dimensions of physical three-dimensional geomechanical model box in this study were 680mm(length) × 350mm (width) × 400mm (height), of which the outer frame was welded by angle iron and the bottom and side plates were made of 2cm thick acrylic material. Also according to the similarity principles, the dimensions of the cross-section of tunnel model were 48mm(tunnel width)×40mm(tunnel side wall height)×90mm(arch radius) and the three-dimensional tunnel model with a length of 320mm was printed by using resin in a 3D printing machine. The karst cave model was simplified as a sphere with a radius of 83mm, which was simulated by two acrylic hemispheres.

Furthermore, according to the geological survey, Xinjie tunnel surrounding rock mass was mainly cut by a set of typical joints with an inclination angle of 12° and a spacing of 2m. As rock joints were the main channels of underground water flow in water inrush accidents, it was crucial to accurately simulate the hydraulic property of rock joint in this model tests. Herein, for simplification, rock joints of the surrounding rock mass of the tunnel were simulated by three layers of fine sand with a thickness of 5mm. However, as it was difficult and time-consuming to pave the fine sand layer in the transparent rock mass material, three layers of fine sand was paved between the right side wall of tunnel and the karst cave in this model tests for the purpose of improving efficiency.

The schematic diagram of the three-dimensional geomechanical model and physical models of tunnel and karst cave were shown in figure 4. When preparing the three-dimensional geomechanical model, transparent rock mass material was put into the model box and compacted slightly with a layer thickness of 5cm each time. The 3D-printed tunnel model was set along the width direction of model box, where some holes were drilled in the tunnel side wall near the karst cave model. The karst cave model was preset in the transparent rock mass material and was connected with a creep pump by transparent soft tube. Some holes were also drilled on the surface of the karst cave model to ensure the flow of water in following water inrush experiment. Three layers of fine sand, which had a thickness
of 10mm and an inclination angle of 12°, were set between the tunnel and karst cave model with a spacing of 30mm.

![Figure 4. Schematic diagram of the three-dimensional geomechanical model. (a) model test box, (b) tunnel model and (c) karst cave model](image)

3.3. Laboratory water inrush test setup

As the karst cave may be filled with water in flood season, the maximum water pressure in the cave was set as 0.3MPa in this study, on the bases of which three levels of water pressure with values of 0.1MPa, 0.2MPa and 0.3MPa were adopted in the water inrush experiments respectively. A creep pump was used to provide steady water pressures in the karst cave by changing the pump speed. During the test, the water pressure in the karst cave was kept constant, and the water flowed out through small holes on the cave surface, then flowing toward the tunnel through the simulated rock joints in the surrounding rock mass model material, finally the water poured into the tunnel through the small holes in the side wall of tunnel model, thus forming a water inrush accident.

In order to monitor the water pressure during water inrush test, high precision pore water pressure sensors were set in the middle layer of fine sand when preparing the three-dimensional geomechanical model, of which the detailed arrangements were shown in figure 5. As shown in figure 5, the water pressure sensors were arranged in the central region between tunnel and karst cave to ensure the accuracy of experimental data. The results of pore water pressure sensors were recorded by a general data acquisition unit, and the flow rates were monitored by weighting the mass of water collecting in the tunnel. The model and equipments of water inrush test were shown in figure 6.

![Figure 5. Plan view of the arrangement of pore water pressure sensors in the three-dimensional geomechanical model](image)

![Figure 6. Model and monitoring equipments of water inrush test](image)

4. Result and discussion
4.1. Water pressure in surrounding rock mass during water inrush process

According to the data of pore water pressure sensors, the change curves of water pressure in surrounding rock mass during water inrush process were shown in figure 7, from which it could be seen that the water pressure of each monitoring point firstly increased with time and then gradually became constant. As the water inrush tests under three levels of initial karst cave water pressure were performed on the same physical model and the initial karst cave water pressure increased hierarchically, the time of the test under initial karst cave water pressure of 0.1MPa was longer than that of the other two levels of initial karst cave water pressure. Also from the results shown in figure 7, it indicated that the water pressure decreased along water flow path that started from the karst cave and ended at the side wall of tunnel. However, in the case that the initial karst cave water pressure was 0.1MPa, the water pressure along water flow path appeared abnormal, that is, the water pressure of point 5 was slightly larger than that of point 4. The reason for this abnormality might be that the sand particles were in the adjustment process, and the sand particles finished this process in following tests under other levels of initial karst cave water pressure condition.

Furthermore, the steady water pressure of each monitoring point during water inrush test would not increase with initial karst cave water pressure, for which the reasons might be that the water would flow around the karst cave under high initial karst cave water pressure, thus resulting in the decrease of water flowing toward tunnel.

4.2. Water inflow rate during water inrush test

During the water inrush test, when the reading of pore water pressure sensor was steady, a glass beaker with a maximum capacity of 500ml was used to collect the water inflow in the tunnel, and the time was recorded when the beaker was full. Based on the data, the water inflow rate could be calculated, from which the change curve of water inflow rate pouring into the tunnel under three levels of initial water pressure of karst cave was derived. According to the curve shown in figure 8, it could be seen that the water inflow rate increased by 84.4% when the initial karst cave water pressure increased from 0.1MPa to 0.2MPa, but the increase rate of water inflow slowed down when the initial karst cave water pressure further increased to 0.3MPa, and corresponding water inflow only increased by 7.2% when comparing with that under the previous level of water pressure.

As rock joints were the main channels for groundwater flow, three layers of fine sand that had good permeability were used to simulate the effect of rock joints during the water inrush test for simplification. As the sand particles would adjust its position under different water pressure, the increasing rate of water inflow under different initial water pressures of the karst cave were different (as shown in figure 8).
5. Conclusion
Taking Xinjie Tunnel of Kaili Ring Expressway in Guizhou Province as an prototype, physical model tests of karst tunnel based on transparent rock mass material were carried out to investigate the water inrush mechanism of karst tunnel. Based on the physical model test results, the following conclusions may be drawn:

(1) During the water inrush tests under each level of initial karst cave water pressure, water pressure decreased along the joints of surrounding rock mass, which indicated that rock joints were the main channels of water inrush between karst cave and tunnel.

(2) During water inrush process, the water inflow rate mainly depended on the initial water pressure of the water-filled karst cave, and the water inflow rate increased by 84.4% when the initial karst cave water pressure increased from 0.1MPa to 0.2MPa, but the increase rate of water inflow slowed down when the initial karst cave water pressure further increased to 0.3MPa, and corresponding water inflow only increased by 7.2%, which indicated that the initial water pressure of karst cave might not be the most important factor on water inrush accident of tunnel.

Furthermore, in this study, rock joints within the surrounding rock mass were approximated by three layers of fine sand, which may cause the deviation of water inflow rate during physical model tests. In future researches, the authors will find a better method to simulate the permeability of rock joint.

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