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Similar simulation experiment of expressway tunnel in karst area

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HIGHLIGHTS

- Tunnel lining and the surrounding limestone rock were studied by similarity theory and orthogonal tests.
- The design, structure, and manufacturing methods for lining, test device, and karst cave were studied.
- Different test cases were designed to analyze the parameters of the designed model.
- The designed model satisfies the constraints, simulates the rainfall conditions.
- The designed model can be used to simulate the effect of karst cave on the tunnel.

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ABSTRACT

According to the actual situation of an expressway tunnel in karst area, the tunnel lining, surrounding rock, and test model were designed by a similar theory and orthogonal experiment. The similarity constants were determined from similar material design experiments. The similar mixture ratio of simulated limestone and tunnel lining was determined using uniaxial compression, triaxial and Poisson's ratio tests. Based on these tests, the structures of lining and karst cave models were designed and analyzed. The data of experimental model were acquired using pore pressure, soil pressure and displacement measuring instruments. Considering the rock joint occurrence, size of cave, cave location, precipitation, loading and other parameters, the pore water pressure, earth pressure, and displacement sensor of experimental model were analyzed under artificial rainfall and loading conditions. The results show that the development of a karst cave affects the tunnel water flow. The test results also show that the experimental model can simulate water penetration and calculate water content.

1. Introduction

The karst area of China is about 1/3 of the land area. In large-scale construction projects of expressway tunnel in China, severe expressway tunnel problems are caused by karst caves. Karst caves around the expressway tunnel easily cause water leakage. Previous projects show that when a karst cave is present behind the tunnel lining, the underground water is poured into the cave along the cracks; the water is then directly poured into the tunnel. Water dissolves the soluble rocks, and under the action of erosion and gravity collapse, cracks and voids can be formed in the surrounding rock [1–3]. Thus, the leakage water of a tunnel in a karst area can accelerate the start and development of all types of related problems.

The tunnels in karst area have been extensively studied [4,5]. The evolution of a karst aquifer was simulated with a coupled continuum flow model [6]. Zhou et al. [7,8] developed a large-scale fluid–solid coupling model. A formulation principle of fluid–solid coupling for similar material was proposed. Under complex geological conditions, the direct effect of a large area of pressurized water and similar materials was evaluated, providing a visual experimental site for the simulation of seepage and water inrush under the fluid–solid coupling condition. Wang et al. [9] studied the water bursting and mud burst of a tunnel and formulated a similar material for the new type of fault and normal surrounding rock. Based on the orthogonal design method, Guan et al. [10]

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performed direct shear and uniaxial compression tests to study the requirements of physical mechanics of a similar rock material and the range of parameters in similar material model test. Liu et al. [11] used iron powder, barite powder, fine sand, gypsum, and glycerol to prepare a similar rock material. The factors affecting the sensitivity of similar material were evaluated by range and variance analyses. Li et al. evaluated the mechanical properties of similar material by uniaxial compressive strength, pseudo three-axial, and Brazil tests [12]. Based on the orthogonal design method, Zhang et al. [13] studied the requirements of similar materials for different rock mass model tests. A similarity model of mechanical properties of rock salt was developed by similarity theory, and the similarity criterion of mechanical parameters was obtained [14]. Wu et al. carried out a series of large-scale similarity model test and numerical simulation of mechanical response of expressway tunnel construction in karst area [15]. The effects of development degree and position of karst cave on the mechanical response of surrounding rock were also analyzed. Yang et al. developed a new type of material made of sand, cement, gypsum, and clay for the simulation of clay plaster [16]. Although a series of research has been carried out in the tunnel disaster model test in karst area, the study of karst tunnel model test and the structure of karst tunnel model are not enough. At the same time, the model test of structural response under the influence of the rock joint dip angle, the diameter of karst cave, the distribution state of karst cave and the distance between the tunnel lining and the tunnel lining have not been reported.

In model experimental studies, the selection of materials and the ratio of similar material are very important. These factors not only determine whether the model can correctly reflect the characteristics of prototype, but also determine the degree of difficulty of model processing and smooth performance of test. In this paper, based on similarity theory and artificial rainfall conditions, a tunnel model was designed and tested. Based on the rationality of the verification test model, the influence of surrounding rock parameter combination on tunnel leakage in karst area is studied. The direction of the development of surrounding rock under the condition of equal cave diameter is analyzed emphatically.

2. Test materials

The test materials were selected according to the similarity theory. To improve the accuracy of test, test materials with good linear elasticity, low elastic modulus, and large bulk density were selected, i.e., fine sand (2 mm in diameter), cement (P.C32.5), clay, barite powder, and water mixture were used as the similar material for limestone. Fig. 1 shows the selected materials. The similar limestone was made using these materials in a rational mix ratio. The mix ratio of materials maintained the physical similarity as much as possible, such as bulk density (γ), elastic modulus (E), Poisson's ratio (μ), and compressive strength (f).

Table 1
Parameter of each level of mixture.

Parameter	Level 1	Level 2	Level 3	Level 4
Cement (g)	180	225	270	315
Fine sand (g)	2700	2850	3000	3150
Clay (g)	600	700	800	900
Barite powder (g)	1800	1850	1900	1950
Water cement ratio (/)	3.60	3.73	3.87	4.0

Table 2
L16 (45) orthogonal experimental design.

Sample number	Cement (g)	Fine sand (g)	Clay (g)	Barite powder (g)	Water cement ratio (/)
1#	180	2700	600	1800	3.60
2#	180	2850	700	1850	3.73
3#	180	3000	800	1900	3.87
4#	180	3150	900	1950	4.0
5#	225	2700	700	1900	4.0
6#	225	2850	600	1950	3.87
7#	225	3000	900	1800	3.73
8#	225	3150	800	1850	3.60
9#	270	2700	800	1950	3.73
10#	270	2850	900	1900	3.60
11#	270	3000	600	1850	4.0
12#	270	3150	700	1800	3.87
13#	315	2700	900	1950	3.87
14#	315	2850	800	1900	4.0
15#	315	3000	700	1850	3.60
16#	315	3150	600	1800	3.73

3. Similar material tests and data acquisition

3.1. Mix ratio of limestone

The mix ratio of similar materials was determined by a mixed-level orthogonal design test. Tables 1 and 2 show the values of each parameter and sample group.

According to the principle of orthogonal test, the test samples were designed and fabricated, as shown in Fig. 2. Based on the test results of uniaxial compressive, triaxial compression, and Poisson's ratio tests (Fig. 3), the mix ratio of similar limestone materials was determined from the specific value of sand, clay, barite powder, and water, i.e., 1:12.67:2.67:8.67:3.87. The test method is based

(a) Selected materials (b) Mixing state of selected materials

Fig. 1. Selected materials and mixing state.