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Numerical simulation to determine the critical safe thickness of water-resisting rock wall based on FLAC3D

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Abstract: Caverns with high pressurized water ahead of tunnel face tend to cause water inrush. So, the determination of the critical safe thickness of the water-resisting rock wall to prevent water inrush geohazard is of great significance during karst tunnel construction. Firstly, to obtain the critical safety thickness of rock wall ahead of karst tunnel face, a numerical model based on FALAC3D and the method to determine the critical safe thickness are established. Then, a series of numerical tests planed by the orthogonal testing theory have been carried out. The rock mass level of rock wall, dip angle of strata, lateral pressure coefficient, cavity scale, water pressure and buried depth of tunnel on the critical safe thickness is studied. Finally, the regressive formula to determine the critical safe thickness of the water-resisting rock wall is established by means of numerical testing results. Taking for examples the Maluqing tunnel on Yiwan railway, the reliability and rationality of the proposed methods were proved, so providing reference for similar engineering projects.

Introduction

It is very impossible that crush rock wall is crushed and high pressurized water inrushes and gushes suddenly under adverse effects (such as karst cave with high pressurized water, underground River, karst conduit and so forth) by excavation disturbance. Therefore, it is significant to determine the safe thickness of rock wall reasonably in construction process of karst tunnel [1-2].

At present, many researches have done a lot of research about the critical safe thickness between the tunnel face and a karst cavity a high pressurized water. GAN Kunrong et al presented the factors that should be considered in the determination of safe thickness of rock wall during construction [3]. the semi-analytical expression of waterproof thickness was reported by Li, et al. [4]. The minimal safe thickness of rock wall was provided based on the catastrophic characters of water inrush by Sun, et al. [5].Guo established the formula to calculate the safe thickness of a rock wall based on critical water pressure [6]. Jiang et al. investigated waterproof-resistant slab minimum safety thickness for water inrush geohazards according to the large-scale geomechanical model test [7].

Considering the disadvantages of many hypotheses in the theoretical analysis and high costs of the model test. In this paper, the numerical simulation methods is employed to investigate the stability of water-resisting rock wall and determine its critical safe thickness, which can well overcome the shortages of research means in the above-mentioned. The research results about the critical safe thickness of rock wall ahead of karst tunnel face are of significant theoretical and practical value to enhance the deep understanding of the water inrush mechanism ahead of tunnel faces, and to prevent this type of water inrush accident.

Numerical model

The calculation range of numerical analysis as follows: the horizontal length of model is 240m; the bottom of model and the top of model are 150m distant from the cave center in vertical direction; then according to the depth of karst cavity, the weight of the upper part of the rock mass model conversion into uniformly distributed load applied on the upper boundary of the model. The bottom of the model is applied displacement boundary constraint conditions, left and right boundary in the model is applied stress boundary constraint, the upper part of the model is free. The tunnel height as the constant is 10m in the calculation model; the cavity inner wall is applied normal stress boundary conditions to simulate the function of water pressure of dissolved cavity.

According to the actual construction situation, the test simulation of tunnel excavation is divided into two stages. The first stage: the tunnel excavation was conducted in six steps and each step is 2m. The tunnel initial support is four meter behind the excavation face and simulated by shell elements. The tunnel face is close to the dissolved cavity at the present; The second stage: the each step of tunnel excavation that started at the end of the first stage excavation is 0.5 meters and the initial support is closed followed by excavation. The damage zone around the cavity and tunnel was examined after the calculation step achieve balance. The distance is safe if the damage zone between the karst cave and the tunnel is not through. The excavation is continued until the damage zone between the tunnel face and the karst cave is though.

For this test, the damage zone between the tunnel face and the karst cave is not connection when the thickness is 6m, but the damage zone is connection when the thickness is 5.5m. Choose S=5.7m as the critical safety thickness. The test accuracy is 0.5m, it could meet the requirement of engineering application.

Influential factors of numerical test and results

The influence factors of the safety thickness between tunnel and cavity mainly includes: (1)the physical and mechanical parameters of rock mass (density γ, elastic modulus E, poisson's ratio v, and internal friction angle φ and cohesion C).(2)the level of peak strength parameters(friction angleφ_1 and cohesion C_1).(3)the dip angle (level and horizontal plane x-z plane angle θ).(4)the lateral pressure coefficient of rock mass λ.(5) the cavity scale D.(6)the water pressure p.(7)the depth of tunnel H.

According to the actual data, the above seven factors are selected in five levels, so the orthogonal test select L_{50} (5^{11}) orthogonal table. The value of influence factor sets in table 1. The calculate results are shown in table 2

Table 1 the value of influence factor

Factor in	Physical and mechanical parameters in rock mass					Level peak strength		Strata inclination	Lateral pressure coefficient	Karst cave diameter	Dissolved cavity Water pressure	Tunnel depth
	λ (KN/M^3)	φ (°)	C(MPa)	E(Gpa)	ν	φ_1(°)	C_1(MPa)	θ(°)	λ	D(m)	p(MPa)	H(m)
1	26.5	47	1.5	15	0.25	35	0.2	-20	1	20	0.6	200
2	25.5	44	1.2	12	0.27	33	0.18	-10	1.25	30	0.8	400
3	24.5	41	0.9	9	0.29	31	0.16	0	1.5	40	1	600
4	23.5	38	0.6	6	0.31	29	0.14	10	1.75	50	1.2	800
5	22.5	35	0.3	3	0.33	27	0.12	20	2	60	1.4	1000

Using multiple regression method to analysis the calculate results, finally get the prediction formula about the safe thickness between karst tunnel and caves

$$S = 5.276e^{0.216A} - 3.076\lambda + 0.1417D - 0.0013D^2 + 3.8883\ln H - 23.2933 \qquad (1)$$

In the formula: A is rock mass level of rock wall $1 \le A \le 5$, λ is the side pressure coefficient of surrounding rock, $1 \le \lambda \le 2$,D is cavity scale (m) $20 \le D \le 60$, H is the buried depth of the tunnel(m) $200 \le H \le 1000$,S is the critical safe distance between tunnel and karst cave(m).

When the surrounding rock grade is III, the value of A is 1~3; when the surrounding rock grade is IV, the value of A is 3~5.

Table 2 Results of numerical simulation tests

surrounding rock in	Level in	Strata inclination (°)	Lateral pressure coefficient	Dissolved cavity tunnel diameter (m)	Dissolved cavity Water pressure (MPa)	Tunnel depth (m)	Critical distance (m)
1	1	-20	1	20	0.6	200	4.8
1	2	-10	1.25	30	0.8	400	5.7
1	3	0	1.5	40	1	600	6.7
1	4	10	1.75	50	1.2	800	7.5
1	5	20	2	60	1.4	1000	7.7
2	1	-10	1.5	50	1.4	200	4.7
2	2	0	1.75	60	0.6	400	6.6
2	3	10	2	20	0.8	600	6.7
2	4	20	1	30	1	800	10.2
2	5	-20	1.25	40	1.2	1000	11.5

Table 2, cont.

3	1	0	2	30	1.2	800	8.8
3	2	10	1	40	1.4	1000	12.3
3	3	20	1.25	50	0.6	200	7.3
3	4	-20	1.5	60	0.8	400	8.4
3	5	-10	1.75	20	1	600	8.9
4	1	10	1.25	60	1	1000	15.6
4	2	20	1.5	20	1.2	200	7.7
4	3	-20	1.75	30	1.4	400	9.2
4	4	-10	2	40	0.6	600	10.2
4	5	0	1	50	0.8	800	18.1
5	1	20	1.75	40	0.8	800	18.2
5	2	-20	2	50	1	1000	17.3
5	3	-10	1	60	1.2	200	12.7
5	4	0	1.25	20	1.4	400	13.3
5	5	10	1.5	30	0.6	600	17.5
1	1	-20	1.75	60	1.2	600	6.6
1	2	-10	2	20	1.4	800	6.2
1	3	0	1	30	0.6	1000	8.7
1	4	10	1.25	40	0.8	200	4.1
1	5	20	1.5	50	1	400	6.7
2	1	-10	1	40	1	400	8.3
2	2	0	1.25	50	1.2	600	8.6
2	3	10	1.5	60	1.4	800	9.5
2	4	20	1.75	20	0.6	1000	9.6
2	5	-20	2	30	0.8	200	5.5
3	1	0	1.5	20	0.8	1000	8.8
3	2	10	1.75	30	1	200	5.2
3	3	20	2	40	1.2	400	8.2
3	4	-20	1	50	1.4	600	13.2
3	5	-10	1.25	60	0.6	800	14.2
4	1	10	2	50	0.6	400	9.2
4	2	20	1	60	0.8	600	18.2
4	3	-20	1.25	20	1	800	14.2
4	4	-10	1.5	30	1.2	1000	13.2
4	5	0	1.75	40	1.4	200	6.4
5	1	20	1.25	30	1.4	600	16.3
5	2	-20	1.5	40	0.6	800	19.1
5	3	-10	1.75	50	0.8	1000	19.1
5	4	0	2	60	1	200	8.7
5	5	10	1	20	1.2	400	13.7

Engineering example

A drain tunnel was builded and the cavity was detected in the Maluqing tunnel after water inrush. The cavity of the I longitudinal karst is DK255+943~+969, and the length is 26m. The cavity of the II longitudinal karst is PDK255+968~+980, and the length is 12m. The drain tunnel is XDK255+982.5～+999, and the length is 17m. The development of lateral is greater than 400m, and development down to the bottom of the tunnel is about 50m, the development of vault is more than 25m. There fills silt clay with gravel and stone, it has large boulders in some area. The rock of the tunnel has strong mechanical strength, the layers is in good condition and no soft interlayer, the grade of surrounding rock is III. The lateral pressure coefficient along the direction of maximum horizontal principal stress is between 0.90~1.44. Calculated the safe thickness by the formula (1) with the parameter (A=1, λ=1.4, D=20, H=200), the calculated results is 1.86m. According to literature [7], the actual thickness of rock wall in Maluqing Tunnel is 1.5m. Combined with the foregoing research conclusions and results of this case, Safe thickness of rock wall by formula (1) is close to the reserved thickness in projects.

Summary

Based on the results of numerical simulation tests planed by the orthogonal testing theory, the regressive formula is established to determine the safe thickness of rock wall ahead of karst tunnel face, which can take account of the rock mass level of rock wall, dip angle of strata, lateral pressure coefficient, cavity scale, water pressure and buried depth of tunnel. Taking the drain cavern of “978 karst cavity” in Maluqing tunnel as the example, the critical safe thickness calculated by the regressive formula in this paper is close to the actual value adopted in project, The formula can be taken as an reliable method for assessing the critical safe thickness of rock wall.

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