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Change Regulation of the Factors Affecting the Upper Plate Stability in Karst Cave with Pile Foundation

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ABSTRACT

The stability of the cave roof under pile foundation is critical consideration for pile design and construction in Karst area. When there is a Karst cave under the pile, the bearing capacity of pile depends on the ultimate bearing capacity of Karst cave roof which is affected by various factors such as cave span, depth of roof and lithologic condition (GSI). The present study is to analyze the change rule of the factors that vitally regulate the stability of the cave roof under pile foundation. It is important for engineer design, construction, cost savings, speed up the construction period. The allowable bearing capacity of the cave roof in various engineering conditions are presented by analyzing determination method of ultimate bearing capacity of the cave roof under pile foundation when the safety K is 2. The linear relationship between ultimate bearing capacity and the width of karst cave, the thickness of upper plate and the mechanical properties of rock mess has been analyzed. The results showed that the negative rate between the ultimate bearing capacity and the width of Karst cave will be improved by the thickness of upper plate, while it would be further decreased with the reducing of rock mass. The other change regulations between the ultimate bearing capacity and influencing factors are obtained.

KEYWORDS：cave roof; finite element analysis; ultimate bearing capacity;; allowable bearing capacity

INTRODUCTION

The commonly analysis methods of cave roof stability under pile foundation on the karst area are mainly composed of semi-quantitative analysis and quantitative analysis. Semi- quantitative analysis method is to simplify the single cavity for the beam, plate and arch model to analysis. Quantitative analysis method commonly used numerical simulation to analyze the stability of karst cave roof. Zhao et al[1-3] establish mechanics model which accord with the characteristics of engineering to further discusses the stability of roof and thickness of the limit. Articles [4-6] studied about how to determine the ultimate bearing capacity of strip foundation above goaf, obtained the determine method and determine the chart of the limit bearing capacity of strip foundation under different conditions .Zhang et al [7]researched the influence of each impact factor of the carrying capacity of rock-socketed pile roof based on the indoor model test, and analyzed the sensitivity of the system .Li [8], Yang [9]et al used finite element algorithm to obtain the relation between pile bottom threshold to the cave at the top of the distance with the size of karst cave and single pile design load. Hu[10]used the finite element method to analysis karst cave roof stability under strip foundation in karst area, obtained under different karst cave span and roof thickness of ultimate bearing capacity of foundation.

Li et al [11] established the numerical model of roof by using three-dimensional numerical simulation software, discussed the relations between the cave stability influence factors . Cao et al[12], Cheng et al [13], studied the relationship between embedded depth of karst cave and size between karst roof stability by joining strength reduction technique.

This paper is based on three typical characteristics of surrounding rock, and using numerical simulation to study cave roof stability under pile ,discuss the relationship between the ultimate bearing capacity with karst cave span and roof thickness, GSI, and obtained the change rule of progressive joint between ultimate bearing capacity and each impact factor.

ANALYSIS AND CALCULATION MODEL

Numerical analysis use ABAQUS6.10. ABAQUS is a large general finite element software , can be simulated calculation for complex analysis model[14]. In order to make the results more representative, numerical calculation use three kinds of typical parameters of rock mass, respectively, I, II and III[15].

Karst cave rock mass mechanics parameters

In this paper, we selected the three typical rock mass parameters that Hoek and Brown et al put forward based on the Hoek-Brown strength criterion (Table 1), Respectively, very hard rock(rock I),medium-intensity rock mass (rock II) and soft rock mass (rock III)[15-17].

Table 1: Material properties for rock mass

Rock mass	I	II	III
Rock strength σ_{ci}(*MPa)*	150	80	20
Geological Strength	75	50	30
Hoek-Brown constant m_b	10.24	2.01	0.66
Hoek-Brown constant α	0.50	0.51	0.52
Friction angle φ(°)	46	33	24
Cohesion c(*MPa)*	13	3.5	0.55
Compressive strength	64.8	13	1.7
Tensile strength σ_t(*MPa)*	0.9	0.15	0.01
Deformation modulus	42000	9000	1400
Poisson's ratio μ	0.2	0.25	0.3
Expansion angle ψ(°)	$\varphi/4$=11.5	$\varphi/8=4$	0

The establishment of the model

The assumptions of this model to simplify the calculation are as follows:(1)The cave rock mass is an isotropic, uniform spatial semi-infinite body located underground;(2)The cave is stable without external load, and the surrounding rock is treated as a continuous elastoplastic;(3)The load applied to the cave is static load, and cycle loading, cyclic loading and their impact on the material are not considered;(4)Cave filling material mechanical properties is low, generally do not bear stress. Therefore, according to the calculation of the empty cave, the result of the analysis is favorable to the filling on the cave stability. Do not consider the role of groundwater.(5)The shape of the cave is considered in terms of the cylinder and is kept in mind.(6)The pile is cylindrical, the pile diameter d = 1.2m, the pile as the end bearing pile to consider, between the pile and soil side friction resistance does not exist; when the pile top load is all transferred to the pile end, and the pile bottom just is below the existence of the cave, the roof is the most unsafe, calculated and analyzed the stability of the cave roof in this state; the analysis does not take into account the destruction of the pile itself

Model calculation area, boundary condition and meshing

According to the theoretical analysis and calculation of the relevant engineering, the boundary in the horizontal direction of the model takes 5 times of the hole, and the bottom boundary takes two times the height of the cave. According to the above assumptions, the calculation of the stability of the roof of the cave is shown in Fig.1.

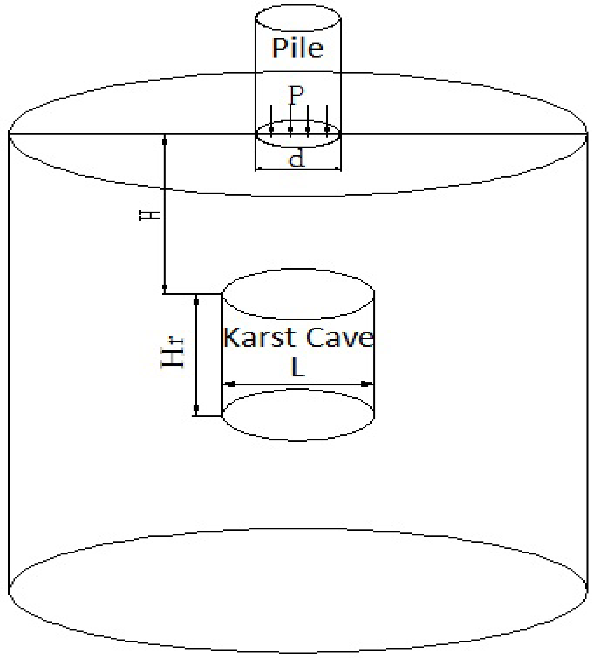


Figure 1: A diagram of calculation

The pile end load is P, the diameter of the piled is d, the cave span is L, the thickness of the roof of the cave is H, the height of the cave is Hr. According to the calculation of the symmetry of the model, take a quarter of the calculation model to calculation, the final establishment of the numerical model shown in Fig..2.

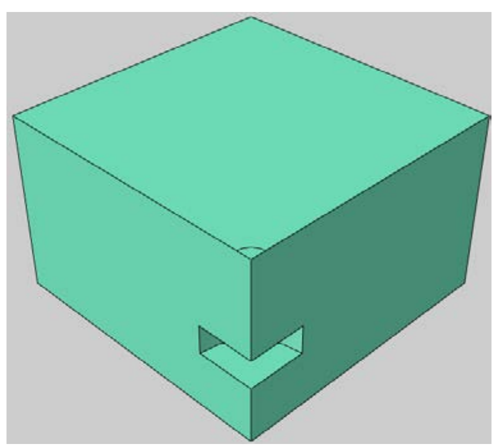


Figure 2: Calculation model

At the bottom of the model, the constraint is fixed at the bottom of the model, that is, no displacement occurs. Horizontal displacement constraints are applied to the outer boundary of the model. Since the boundary of the model is 5 times the corresponding geometric size of the cave, it can be concluded that the horizontal displacement constraint is 0, The symmetry of the two symmetry surfaces is used. The grid unit uses the eightnode hexahedral element, the C3D8R cell, and the meshing is shown in Fig.3. The pile top load is loaded into the bottom of the pile foundation through the stages of loads until the top of the cave has a plastic zone through.

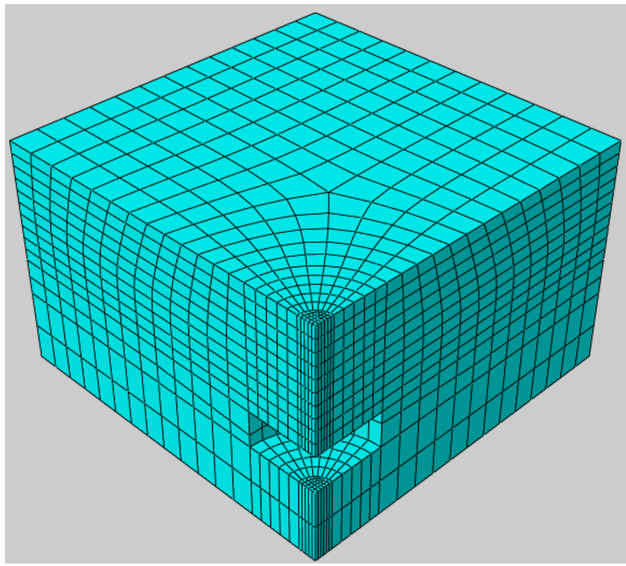


Figure 3: Mesh of calculation model

DETERMINATION OF BEARING CAPACITY OF ROOF

In this paper, the critical thickness of the cave roof under different conditions is analyzed by analyzing the ability of the roof of the cave to bear the pile load under different cave size and depth. The most commonly method to determine the ultimate bearing capacity in the current project is to give the relationship between the load P and the base center displacement S by the field load test or the numerical simulation. The ultimate bearing capacity is determined according to the P-S curve. The most common method of determining the bearing capacity is as follows[18].

(1)Vesic[19] thinks that the slope of the P-S curve is equal to 0 or stored in a constant minimum point is the ultimate bearing capacity.

(2)Lin[20] proposed two methods:①Turning point method, when the test to meet the termination conditions of rock and soil, P-S curve on the obvious turning point is the ultimate bearing capacity;②Semi-logarithmic method, not directly using the P-S curve, but in the P-LnS or LnP-S curve, the latter is generally a straight line, the straight line of the starting point is the ultimate bearing capacity.

The yield failure of rock mass is related to geotechnical properties , cave geometry and its relative position. In this paper, the method of determining the ultimate bearing capacity of the roof is as follows:(1)The plastic zone reaches the load at the top of the cave;(2)The ultimate bearing capacity is determined by the semi - logarithmic method. Take the smaller value as the ultimate bearing capacity

Model calculation scheme

The influence factors of surrounding rock characteristics, roof thickness, cave span and cave height are analyzed in this paper.

In order to study the influence of cave span on ultimate bearing capacity, this paper introduces the ratio n of hole and hole height. The definition of n is

$$n = L / d \quad (1)$$

In this case, L is the cave span and d is the diameter of the pile,d take a value of 1.2m,n is six values, respectively, 1,2,3,4,5 and 6, respectively, corresponding to the cave span of 1.2m, 2.4m, 3.6m, 4.8m, 6m and 7.2m. Fixed non-analytical factors, the analysis of factors to take a number of values for calculation and analysis, derived from the ultimate bearing capacity and the influencing factors of the law.

CALCULATION RESULTS AND ANALYSIS

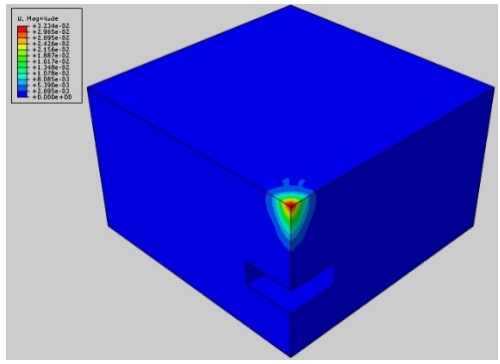
Graphical results analysis

When the cavern height Hr is 1d = 1.2m, the roof thickness H is 5m, n = 2 is the cave span L is 2.4m, the rock mass III is subjected to the numerical simulation of the graded load on the bottom of the pile foundation to obtain the roof displacement, stress and plastic strain map.

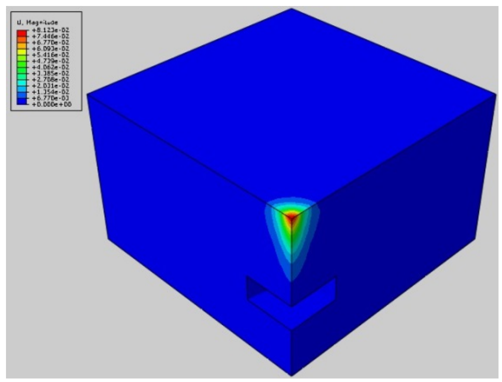
It can be seen from Fig. 4 to Fig. 6 that when the plastic zone of the roof is penetrated, the influence of the pile load in the horizontal and vertical directions does not exceed the calculation area of the model, indicating that the division of the calculation area is reasonable.

(1) Displacement analysis

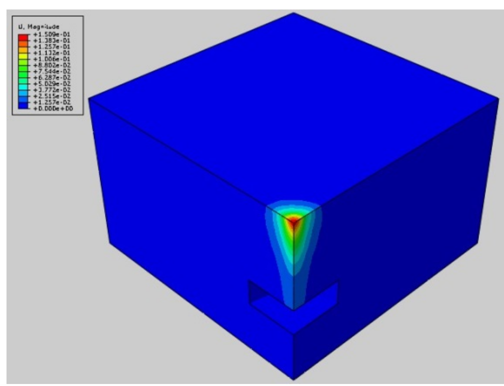
Fig.4 for the loading began to the top of the plastic zone through, calculate the displacement of the model map. It can be seen from the figure that the displacement of the roof of the cave is generally downward, and the displacement within the working range of the pile is obviously larger than that of other regions. The deformation of the pile bottom is basically vertical and downward, both sides to the lower left and lower right respectively, and its influence range gradually extends from the bottom of the pile down to the bottom of the roof.



a Displacement Equivalent Cloud Diagram with Load of 1 MPa



b Displacement Equivalent Cloud Diagram with Load of 1.5 MPa

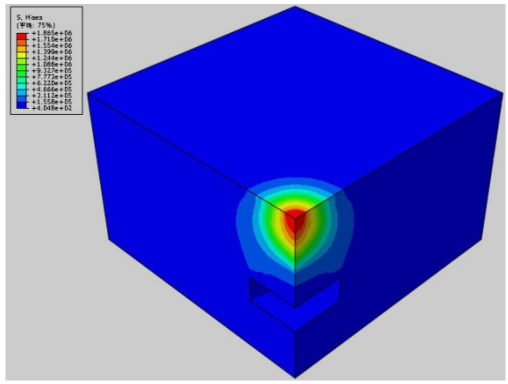


c Displacement Equivalent Cloud Diagram for Ultimate Bearing Capacity

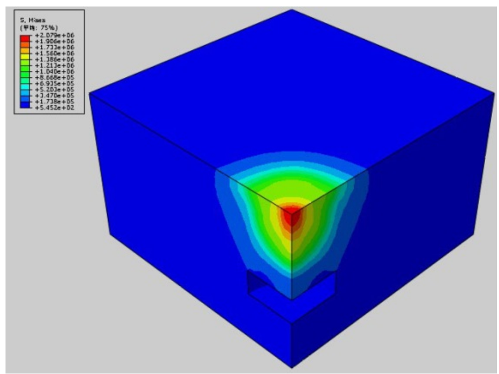
Figure 4: Displacement equivalent nephogram when the thickness of upper plate H is 5 meters

(2) Stress Analysis

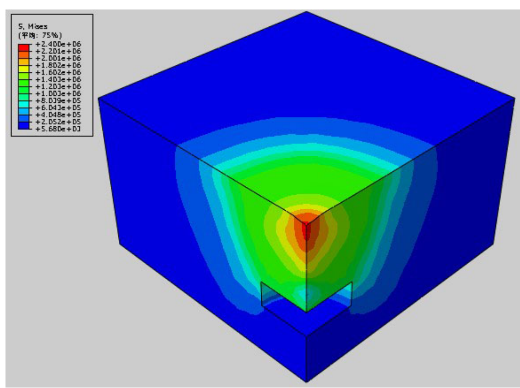
Fig. 5 shows the stress change of the model from the beginning of loading to the penetration of the plastic zone in the roof. It can be seen from the figure, the roof of the cave roof is under the load of the pile, the top of the pile above the pile is under the stress concentration, the top of the roof at the center of the maximum stress in the cave around the stress concentration did not appear.



a Stress equivalent cloud at 1MPa load



b Stress equivalent cloud at 1.5MPa load

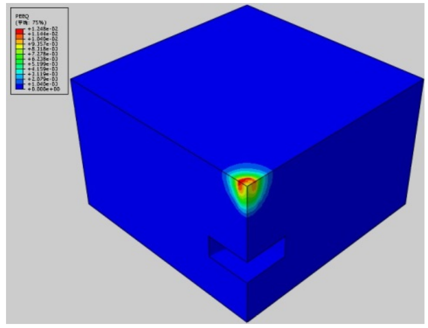


c Stress - equivalent cloud image at ultimate load - carrying capacity

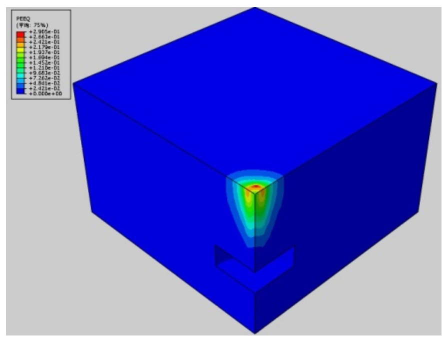
Figure 5: Stress equivalent nephogram when the thickness of upper plate H is 5 meters

(3) Plastic zone analysis

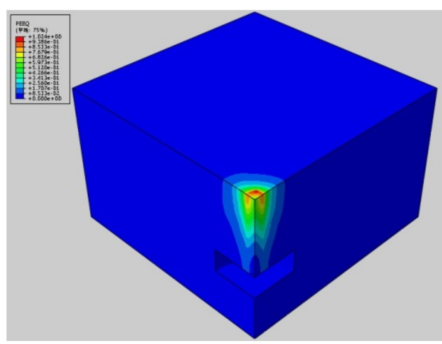
Fig.6 shows the plastic strain diagram of the model through the start of loading to the plastic zone in the top plate. As can be seen from the figure, with the increase of load, some areas of the roof of the cave began to appear plastic change, the pile foundation edge first appeared plastic zone, and then to the pile of rock and the roof rock body expansion, until the plastic strain appears at the bottom of the top plate, that is plastic area through, according to determine the conditions, concluded that the roof has reached the limit state, stop loading.



a The plastic strain equivalent cloud image when the load is 1MPa



b The plastic strain equivalent cloud image when the load is 1.5MPa



c Plastic strain equivalent cloud at ultimate load

Figure 6: Plastic strain equivalent nephogram when the thickness of upper plate H is 5 meters

Analysis of ultimate bearing capacity

Under the above conditions, when the plastic zone reaches the top of the cave, the base pressure P reaches 2.29MPa, and the center point of the bottom plate of the pile foundation is selected as the key point..Draw the LnP-S curve of the calculation scheme. As shown in Fig. 7, the ultimate bearing capacity determined by the semi-logarithmic method is 1.98MPa. Based on the two results, the ultimate bearing capacity Pu is 1.98MPa.

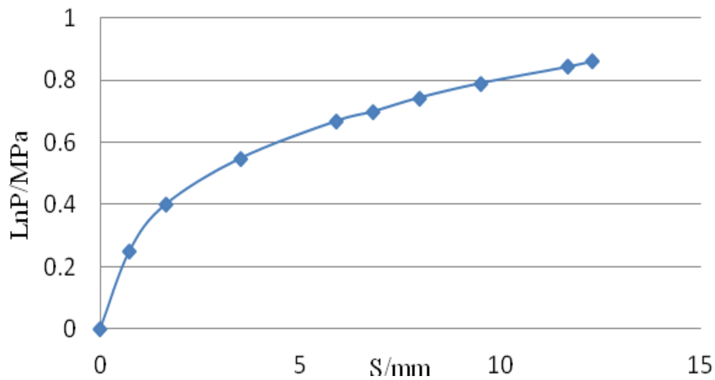


Figure 7: LnP-S curve of the center of the upper plate When the thickness of upper plate H is 5 meters

According to the determination method of ultimate bearing capacity, the ultimate bearing capacity of roof can be obtained under various calculation schemes. According to the *Technical Code for Building Pile* (JGJ94-2008), the safety factor K = 2 [21], the permissible bearing capacity of the roof of the cave and the variation between the cave span, the roof thickness and the lithology condition are shown in Table 2.

Table 2: The results of the allowable bearing capacity

a Rock mass I (MPa)

H/m	*n*=3	*n*=4	*n*=5	*n*=6
3.5	63.72	59.34	57.73	54.58
4	83.24	78.25	74.39	70.98
4.5	104.10	98.51	92.43	88.77
5	127.46	121.15	112.73	108.71
5.5	151.88	144.71	133.79	129.27
6	177.93	167.32	151.34	143.73
No cave	209.25			

***Table 2** continues on the next page...*

C

b Rock mass II (MPa)

H/m	*n*=2	*n*=3	*n*=4	*n*=5	*n*=6
3.5	7.03	6.09	5.42	4.97	4.67
4.0	9.10	8.24	7.44	6.97	6.57
4.5	11.50	10.58	9.49	8.87	8.22
5.0	14.42	13.49	12.19	11.47	10.63
5.5	17.19	16.30	14.82	14.03	13.05
6.0	20.28	19.30	17.52	16.55	15.29
No cave			24.29		

c Rock mass III (MPa)

H/m	n=1	n=2	n=3	n=4	n=5	n=6
3.5	0.76	0.63	0.52	0.43	0.40	0.34
4.0	0.87	0.75	0.64	0.55	0.49	0.44
4.5	0.99	0.87	0.76	0.66	0.57	—
5.0	1.08	0.97	0.88	0.78	0.68	—
5.5	1.16	1.07	1.00	0.90	0.79	—
6.0	1.24	1.17	1.12	1.05	—	—
No cave				1.33		

Influence of Cave Height on Ultimate Bearing Capacity of Roof

When the cave span L and the roof thickness H are constant ,and the height of the cave is changed, the rock mass is calculated and analyzed, and the ultimate bearing capacity of the roof is obtained. Calculation of n take 4, that is, L is 4.8m, cave height were taken as 0.5d(d is the pile diameter,d=1.2m,)1d, 1.5d, 2d, 2.5d and 3d, and the rock mass is rock mass III , the geological strength index GSI = 30, cohesion c = 0.55Mpa, internal friction angle = 24° , elastic modulus E = 1.4GPa, Poisson's ratio μ = 0.3. According to the method of determining the ultimate bearing capacity, the calculation results of the ultimate bearing capacity of the roof are shown in Table 3:

Table 3: Ultimate bearing capacity of cave roof under different height of cave

H(m)	0.5d	1d	1.5d	2d	2.5d	3d
Pu(MPa)	1.81	1.797	1.792	1.789	1.782	1.758

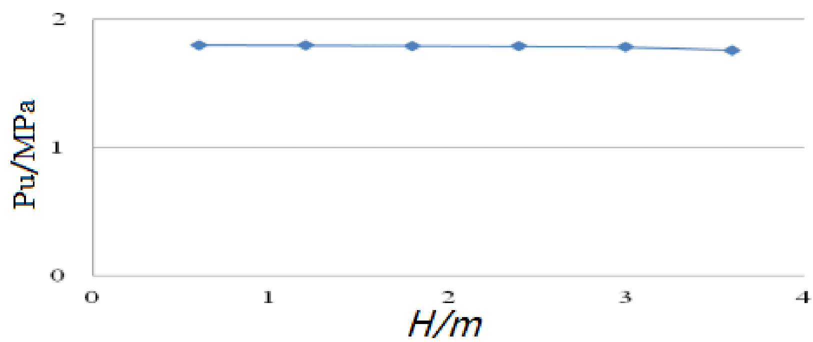


Figure 8: Variation of ultimate bearing capacity with height of cave

Under this condition, the relationship between the ultimate bearing capacity of the roof and the height of the cave is shown in Fig.8. It can be seen from Table 3 and Fig. 8 that the height of the cave has little effect on the ultimate bearing capacity of the roof. Therefore, the back of the analysis, the height of the cave are set by 1d.

Influence of Cave Span on Ultimate Bearing Capacity of Roof

The height of the cave is Hr = 1.2m, the thickness of the cave roof is increased from 3.5m to 6m, and the span ratio n is 1, 2, 3, 4, 5 and 6 respectively. Under three different lithologic conditions,the relationship between the ultimate bearing capacity P_u of the cave roof and the cave span L is shown in Fig.9.

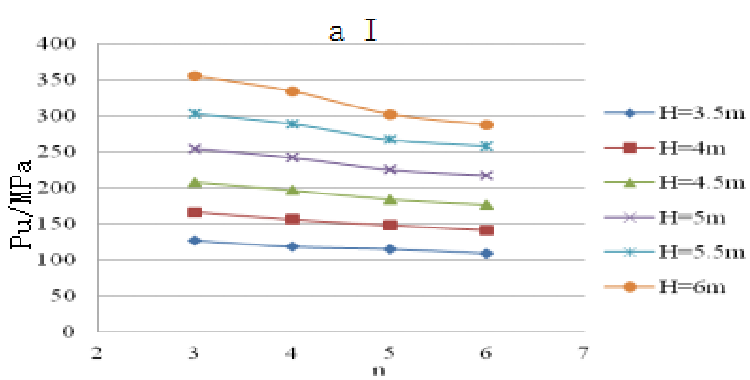
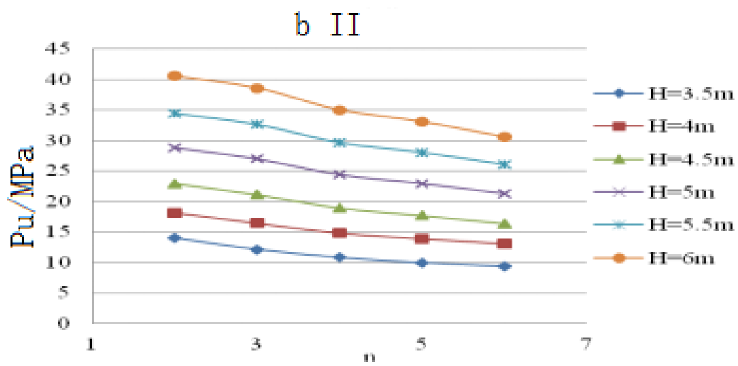


Figure 9: *Continues on the next page*



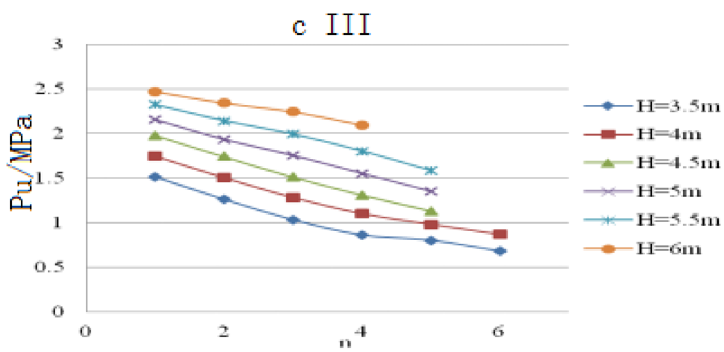


Figure 9: Variation of ultimate bearing capacity with width of cave under different GSI

Fig.9 shows that for three typical rock mass, when the thickness of the cave roof is constant, the ultimate bearing capacity is inversely proportional to the cave span: the cave span increases and the ultimate bearing capacity decreases.

From Fig. 9a, for the rock mass I, when the thickness of the roof is H = 3.5m, the span ratio n increases from 3 to 6, the ultimate bearing capacity Pu decreases from 127.43MPa to 109.15MPa, and the decreasing rate is 6.09MPa / n;And so on can be drawn that the ultimate bearing capacity of the roof with the increase in the rate of reduction and the thickness of the roof and the relationship between the strength of rock as shown in Table 4:

Table 4: Relationship between variation of ultimate bearing capacity with width of cave and thickness of upper plate and GSI

H/m	Reduce the rate/MPa/n		
	Rock mass I	Rock mass II	Rock mass III
3.5	6.09	1.18	0.15
4	8.17	1.26	0.17
4.5	10.22	1.64	0.20
5	12.50	1.90	0.19
5.5	15.07	2.07	0.19
6	22.80	2.50	—

From the analysis of Table 4 and the results, it can be seen that the decrease rate of the ultimate bearing capacity of the roof increases with the increase of the thickness of the roof ,the greater the thickness of the roof, the ultimate bearing capacity decreases as the cave span increases. The decrease of the ultimate bearing capacity of the roof decreases with the decrease of the rock mass strength, that is, the lower the rock mass strength, the lower the ultimate bearing capacity decreases with the increase of the cave span.

Influence of roof thickness on ultimate bearing capacity of roof

Fig.10 shows the relationship between the ultimate bearing capacity Pu and the thickness H of the roof under three lithologic conditions. It can be seen from the figure that when the cave span is constant, the thickness of the roof is significantly affected by the ultimate bearing capacity of the roof.

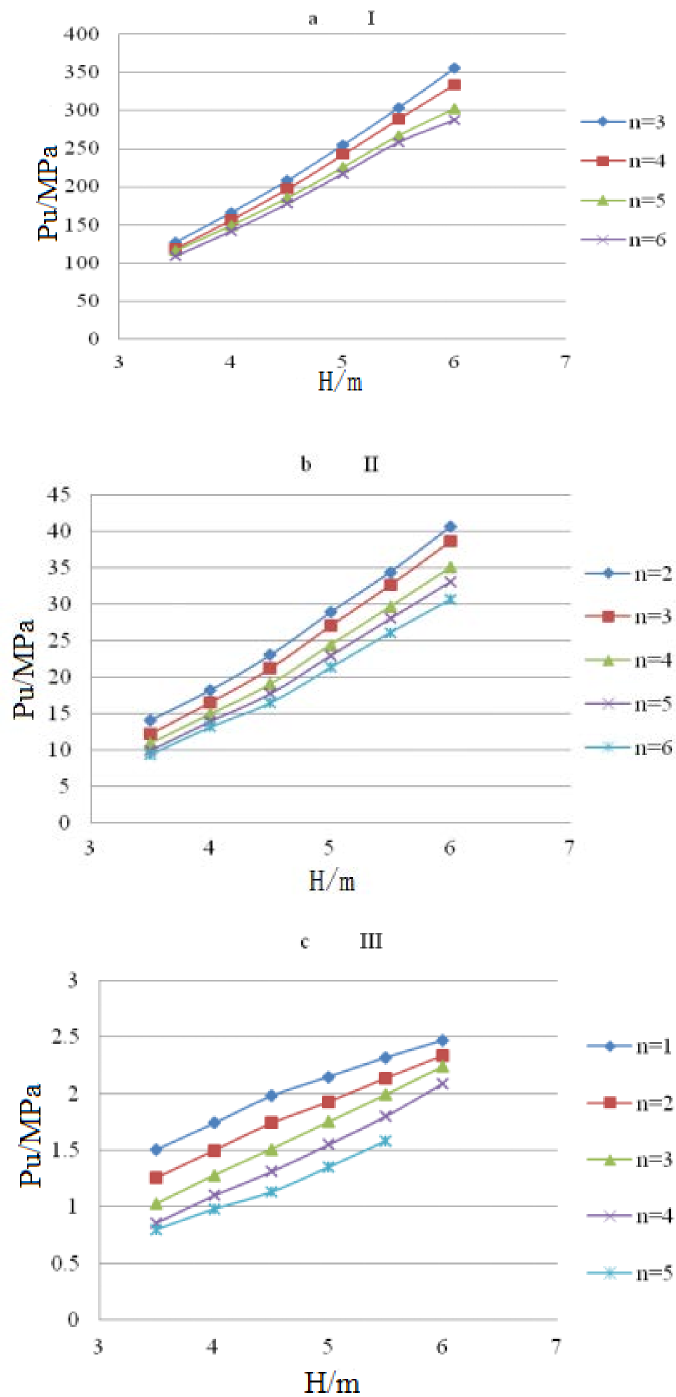


Figure 10: Variation of ultimate bearing capacity with thickness of upper plate under different properties of rock mass

Fig.10 shows that for the three typical rock mass, when the cave span is constant, the ultimate bearing capacity is linearly proportional to the thickness of the cave roof：The ultimate bearing capacity increases with the increase of roof thickness

It is known from Fig. 10a that for the rock mass I, when the span ratio n = 3, the thickness of the roof increases from 3.5m to 6m, the ultimate bearing capacity Pu increases from 127.43MP to 355.86MPa, the increase rate is 91.37MPa / M; By analogy, we can draw the conclusion that the ultimate bearing capacity increases with the increase of the thickness of the roof and the relationship between the span of the cavern and the strength of the rock mass, as shown in Table 5

Table 5: Relationship between variation of ultimate bearing capacity with thickness of upper plate and width of cave and GSI

N	Increase the rate/MPa/m		
	Rock massI	Rock massII	Rock massIII
1	—	—	0.38
2	—	10.6	0.43
3	91.37	10.57	0.48
4	86.39	9.68	0.49
5	74.88	9.26	—
6	71.32	8.5	—

From Table 5 and the above analysis, for rock mass I and II, the rate increases with the thickness of roof bearing capacity limit decreases with the increase of the span of the cave, the cave span increases, with increasing thickness of roof increases more slowly the limit bearing capacity of roof; For rock mass III, the rate increases with the thickness of roof bearing capacity limit but increases with increasing the span of cave, cave span is bigger, faster increases with the thickness of roof bearing capacity limit. The ultimate bearing capacity increases with the increase of the thickness of the roof, which decreases with the decrease of the strength of the rock mass

Influence of strength of cave rock mass on ultimate bearing capacity of roof

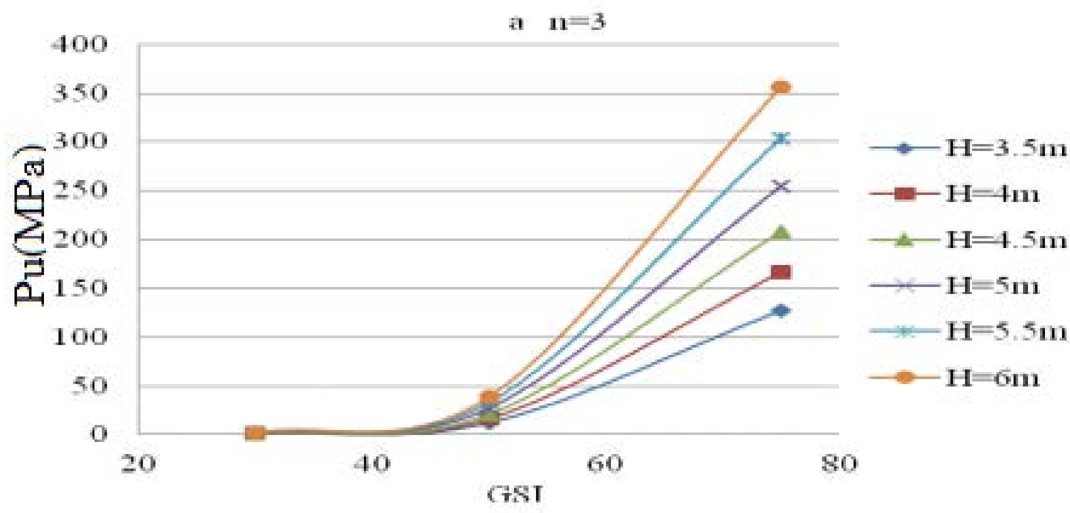


Figure 11: Variation of ultimate bearing capacity with GSI under the width of cave

Fig.11 shows the relationship between the ultimate bearing capacity of the top plate and the GSI when n = 3, 4, 5 (only n = 3), and the thickness of the roof is between 3.5m and 6m. From the figure, when the cave span is constant, GSI significantly affects the ultimate bearing capacity of the roof

Fig.11 shows that, even if the roof is thick, when the cave span is constant, the ultimate bearing capacity of the roof increases with the increase of GSI, the greater the GSI, the faster the growth rate. The thicker the roof, the faster the growth rate

As can be seen from figure 11a, for the span ratio n=3, when the roof thickness of h=3.5m, GSI were 75 and 30,50, the ultimate bearing capacity of the roof PU were 1.03MPa, 12.18MPa and 127.43MPa, the rate of increase was 0.56MPa/gsi and 4.61MPa/gsi, respectively; And so on can be drawn to limit the ultimate bearing capacity of the roof with the increase in the rate of increase and the cave span and roof thickness of the relationship between the table as shown in Table 6.

Table 6: Relationship between variation of ultimate bearing capacity with GSI and width of cave and thickness of upper plate

H/m	Increase the rate/MPa/GSI							
	n=3		*n*=4		*n*=5		*n*=6	
	30→50	50→75	30→50	50→75	30→50	50→75	30→50	50→75
3.50	0.56	4.61	0.50	4.31	0.46	4.22	0.43	3.99
4.00	0.76	6.00	0.69	5.66	0.65	5.39	0.61	5.15
4.50	0.98	7.48	0.88	7.12	0.83	6.68		6.44
5.00	1.26	9.12	1.14	8.72	1.08	8.10		7.85
5.50	1.53	10.85	1.39	10.39	1.32	9.58		9.30
6.00	1.82	12.69	1.65	11.98		10.78		10.27

notes： In the table→Mean to increase. That is 30 to 50 indicates that GSI increased from 30 to 50.

From table 6 and the above analysis, we can see that the ultimate bearing capacity increases with the increase of GSI, which increases with the thickness of the roof, that is, the greater the thickness of the roof, the faster the ultimate bearing capacity increases with the increase of GSI

Fig.12 is the top plate when the thickness of 3.5m, 4m, 4.5m, 5m, 5.5m and 6m (this figure only lists the top plate thickness of 3.5m), n between 3 to 6 changes, the ultimate bearing capacity And the relationship between the GSI curve. It can be seen that GSI significantly affects the ultimate bearing capacity of the roof when the thickness of the roof is constant.

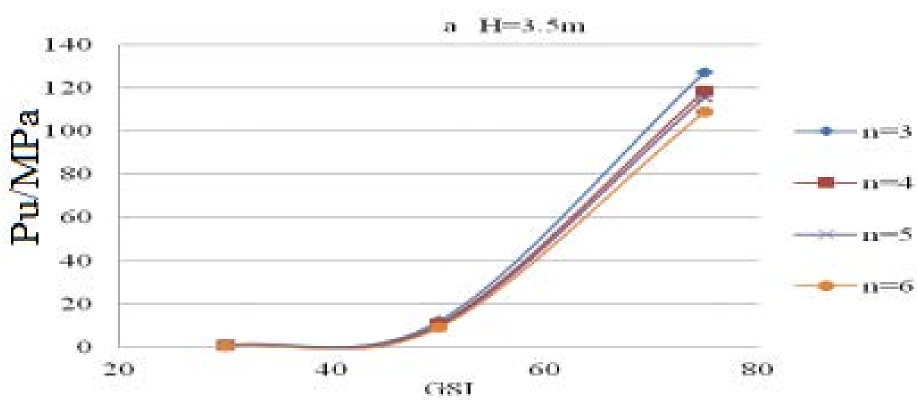


Figure 12: Variation of ultimate bearing capacity with GSI under the thickness of upper plate

Fig.12 shows that no matter how large the span of the cave, when the roof thickness is unchanged, the ultimate bearing capacity of the roof increases with the increase of GSI, and the greater the GSI, the faster the growth rate

It can be seen from Figure 12 and table 6 that the rate of ultimate bearing capacity increases with the increase of GSI and decreases with the increase of the span of the cave, that is, the larger the span, the slower the ultimate bearing capacity increases with the increase of GSI

SUMMARY AND CONCLUSIONS

Based on the characteristics of the study object, the numerical simulation is carried out using the nonlinear elastoplastic model, the Drucker-Prager yield criterion and the numerical simulation software ABAQUS6.10. According to the yield criterion and constitutive relation, and the reasonable assumptions of the model, the span of the cave, different height, different thickness, different lithology conditions, stress conditions of cave roof under pile foundation loading are studied by numerical analysis, the bearing capacity and ultimate cave span, variation of roof thickness and rock strength the conclusions are as follows

(1) The height of the cave has little effect on the ultimate bearing capacity of the roof

(2) The ultimate bearing capacity of karst cave roof is inversely proportional to the span of the cave. With the increase of the thickness of the roof, the ultimate bearing capacity of the roof increases with the increase of the thickness of the roof, and decreases with the decrease of the strength of the rock mass

(3) The ultimate bearing capacity is nearly linear proportional to the thickness of the roof. The rate at which the ultimate bearing capacity increases with the increase of the thickness of the roof decreases with the decrease of the rock mass. For the rock mass I and rock mass II, the ultimate bearing capacity increases with the increase of the thickness of the roof and decreases with the increase of the span of the cavern; However, for rock mass III, the rate of ultimate bearing capacity increases with the thickness of the roof increases with the increase of cave span.

(4) When the cave span is constant, the ultimate bearing capacity of the roof increases with the increase of GSI, and the bigger the GSI, the faster the growth rate, the thicker the roof, the faster the growth rate. When the roof thickness is unchanged, the ultimate bearing capacity of the roof increases with the increase of GSI, and the larger the GSI, the faster the growth rate, the greater the span of the cave, the slower the growth rate

(5) When the safety factor $K = 2$ is taken, the allowable bearing capacity of the roof is obtained.

(6) Based on the above conclusions, combined with the corresponding safety factor, we can determine the allowable bearing capacity of karst cave roof in practical engineering, and then determine the safe thickness of karst roof.

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