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RESEARCH ARTICLE

Study of the Critical Collapse Cave Span for Fracture-cavity Oil Storage Karst Caves

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Abstract: As the major field in petroleum reserve growth, fractured-vuggy reservoir is the key research in the future. However, in the development of fracture-cavity reservoir, collapse may occur in karst cave which greatly affects the oil well output. In order to forecast the cave collapse before drilling, this work adopts the method of span dichotomy reduction to determine the critical karst collapse of the fracture-cavity reservoir cave on the background of Tahe Oilfield's fractured-vuggy reservoir. Different factors which influence on the tunnel span of karst collapse and the failure modes of collapsed cave are obtained by great amounts of numerical calculation and analysis on working conditions. Research results in this work provide significant theoretical evidence to the oil exploration in Tahe Oilfield's fracture-cavity reservoir.

Keywords: Critical Collapse Span, Collapse Span, Fractured-vuggy Reservoir, Method of Span Dichotomy Reduction, Numerical Calculation, Predictor Formula.

1. INTRODUCTION

regarding typical carbonate reservoir, the Ordovician reservoir in Tahe Oilfield is the super-huge, ultra-deep and low-abundant heavy oil reservoir with buried depth of 5300 m~6200 m. According to drilling and logging records, secondary caves act as the principle reservoir space and unfilled karst caves in the earth reach a few meters or much deeper, while the filled caves can be up to dozens of meters [1, 2]. However, collapse occurs in oil exploration, which greatly affects the well yield and the recovery efficiency of oil reservoir [3, 4]. Therefore, it is greatly significant to develop quantitative research on the size of collapse in carbonate reservoir underground.

The previous research on the collapse of fracture-cavity reservoir and the span of cave includes mainly the following aspects. Deng [5] proposed detailed treatment measures on blowing off the dropout phenomenon in carbonate reservoirs by researching the Tahe Oilfield. In addition, rational suggestions were proposed on oil exploration and further understanding on the fracture-cavity reservoir in Tahe. Zheng *et al.* [6] drew the quantitative domain of collapse depth according to the fundamental of rock mechanics, providing an theoretical basis for the quantitative understanding on collapse depth of fracture-cavity reservoirs. Zhang *et al.* [7] concluded the relationship between roof thickness and collapse cave span by numerical modeling of damage process of roof in goaf. In conclusion, some achievements on loss mechanism, development technology and phenomenon description of collapse of fracture-cavity reservoirs have been obtained, but the quantitative understanding on collapse cave span of fracture-cavity reservoirs is still vague.

Therefore, this work adopted theoretical analysis and numerical simulation for the critical collapse cave span to provide important theoretical basis for oil exploration of fracture-cavity reservoirs in Tahe by gaining failure modes and influence factors of collapse.

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2. METHOD OF SPAN DICHOTOMY REDUCTION BASED ON NUMERICAL CALCULATION

2.1. Numerical Analysis Model and Computational Condition

Major factors affecting collapse cave include: tunnel span of karst cave L and roof thickness h. Fig. (**1**) shows the numerical analysis model and boundary conditions of karst cave. The additional stress caused by the weight of overlying rock on the roof of cave is replaced with the vertical stress $P=\gamma H$ which refers to the product of the average volume-weight of stratum γ multiplied by actual buried depth H.

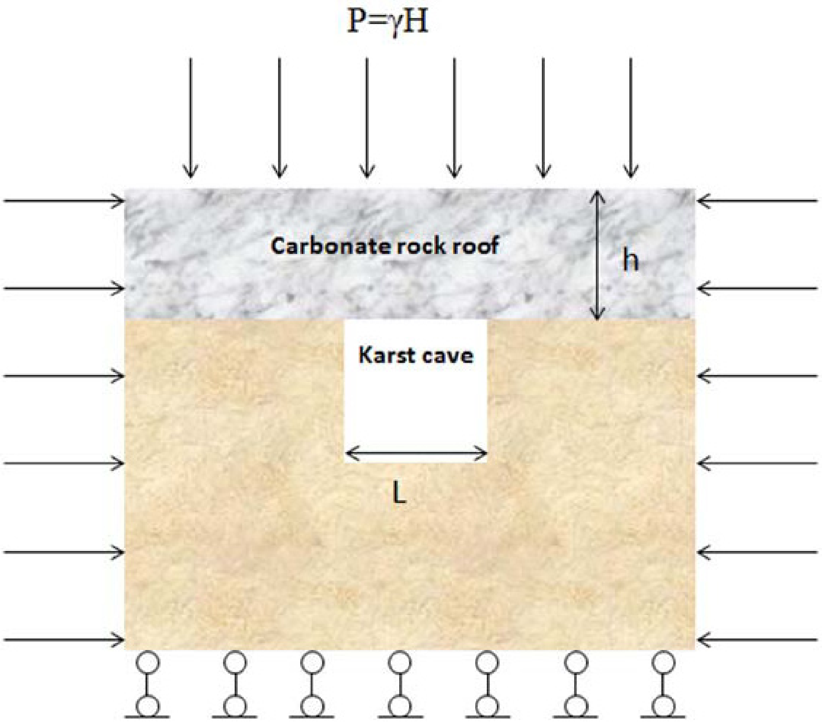

Fig. (1). Numerical model and boundary conditions of karst cave.

The vertical stress $P=\gamma H$ is applied on the top of the model. Horizontal stress is applied on both sides of the model. The horizontal stress gradient is T_h = 0.0155 MPa/m, and vertical stress gradient is T_v= 0.025 MPa/m [8]. Considering the effect of constraint boundaries both sides of cave should be stretched to five times, and the bottom is chosen as the constraint boundary. Table **1** lists the physical and mechanical parameters of carbonate rock.

Table 1. Physical mechanical parameters of carbonate rock.

Bulk Density (kN/m^3)	Poisson's Ratio	Modulus of Elasticity (Gpa)	Compressive Strength (MPa)	Tensile Strength (MPa)	Angle of Internal Friction (^{o})	Cohesive Force (MPa)
27	0.25	36.3	74.2	3.8	36.05	2

2.2. Determination of Critical Collapse Cave Span by Method of Span Dichotomy Reduction

The reduction method for critical collapse span of karst cave proposed in this work learns from the calculation of slope safety factor. In other words, the critical damage state which can be achieved by adjusting the tunnel span of karst cave with other conditions constant is the critical collapse span. However, the computational process is complex and the accuracy of results cannot be guaranteed by stepwise solution, so optimized dichotomy is adopted to deal with this problem in this work. The specific flow is shown in Fig. (**2**).

According to Fig. (**2**), one can first choose the upper and lower limits ($L_1$and L_2) of tunnel span and the initial tunnel span (L) which is the mean of upper and lower limits L, and then numerical analysis is conducted for karst cave. If collapse does not occur at this time, numerical flow should continue with L as the lower limit and L_2 as upper limit until collapse occurs.

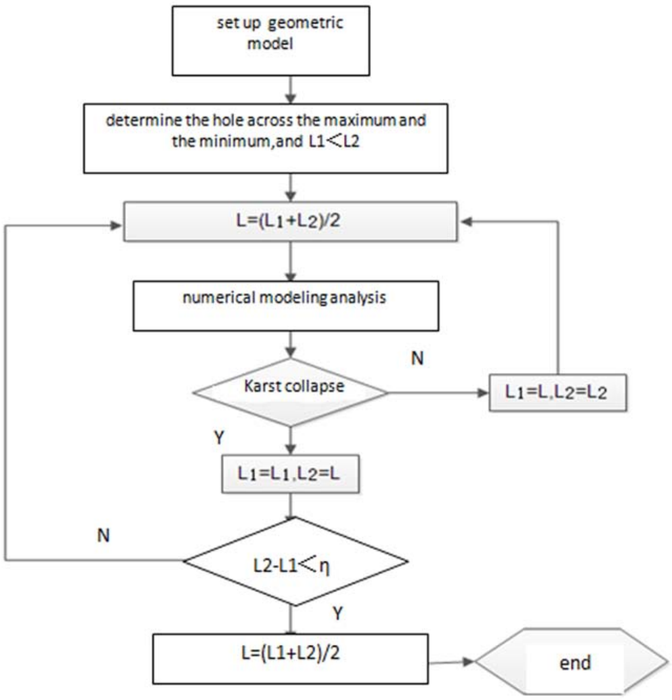

Fig. (2). Solving flowchart of critical collapse karst cave span.

However, the critical tunnel span is not the collapse span by this time. It should be judged if the difference between upper and lower limits meets the error requirement. If the difference is not met, the upper and lower limits should be treated with using dichotomy method until the difference meets the error requirement. At this time, the mean value of the upper and lower limits is the critical collapse span.

The method of span dichotomy reduction mentioned above can be used to determine the critical collapse cave span, controlling the accuracy of the critical collapse cave span and simplifying the calculational process.

2.3. Calculation Results of Collapse Span Affected by Single Factor

Take a set of results as an example due to large amounts of calculation results. Given that the proof thickness is 25 m, the buried depth is 5600 m and tunnel span is 10 m, one can obtained the flowchart of cave collapse as Fig. (**3**) by the numerical analysis model as Fig. (**2**).

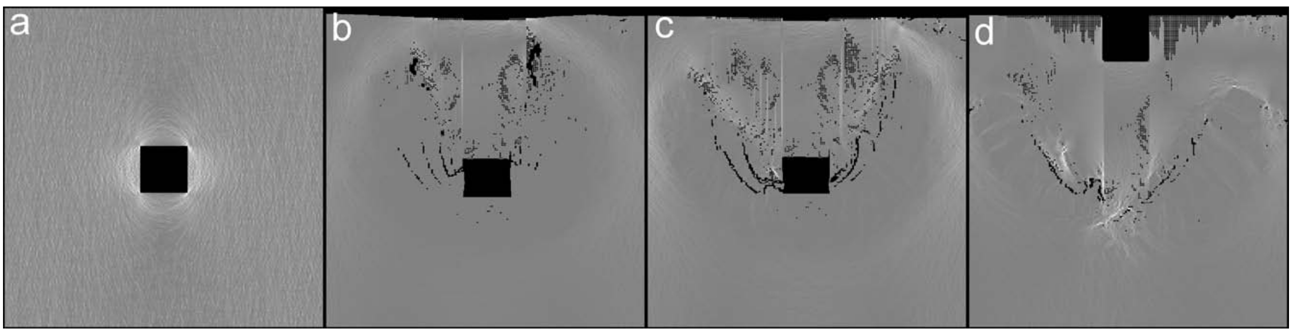

Fig. (3). Collapse-failure process of rectangle cave.

Fracture firstly occurs at both sides of the collapse cave and develops continuously upward, see Fig. (**3**). The roof of the cave moves downward until destroys. Under the action of high geostress, several shear fractures running through the cave roof will form, causing the collapse and damage of the whole cave.

With the method of span dichotomy reduction to calculate the critical collapse span in Section 2.2, the curve of critical collapse span changing with roof thickness and buried depth is shown in Fig. (**4**).

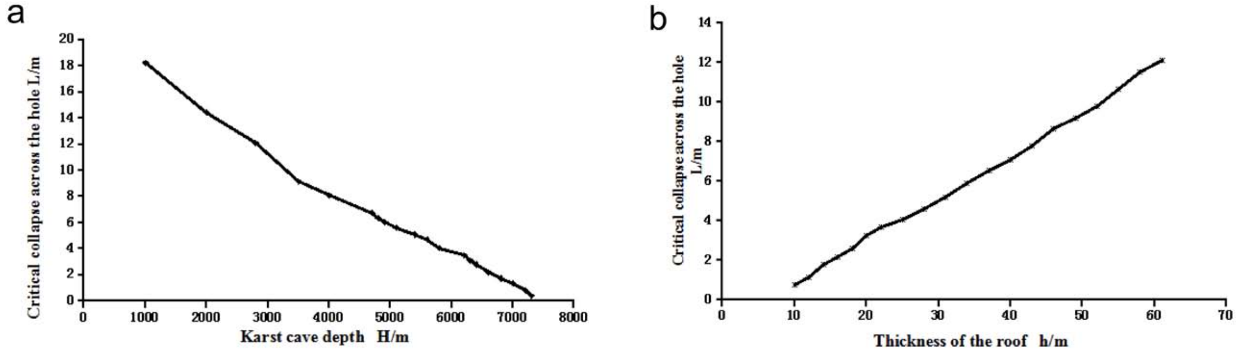

Fig. (4). Relation curves of critical collapse span to various factors.

In accordance with Fig. (**4**):

1) The collapse span decreases with the increase of buried depth. In other words, the larger the buried depth is, the smaller the critical collapse span will be and more easily the cave will collapse.

2) The critical collapse cave span enlarges with the increase of roof thickness. In other words, the larger the roof thickness is, the larger the critical tunnel span will be and the more difficult the cave will collapse.

Second-order polynomial fitting are adopted to obtain the relationship between different influence factors and collapse span. Moreover, the optimal relationship between different influence factors and tunnel span in collapse, as well as the changing curves are determined as shown in Table **2** and Fig. (**5**), respectively.

Table 2. Relations between critical collapse cave span and roof thickness and depth.

Impact Factor	Best Relational Expression	Correlation Coefficient
Karst cave depth H	$L = 1\times10^{-7}H^2 - 0.0038H + 21.679$	0.996
the thickness of the roof (h)	$L = 0.0004h^2 + 0.1916h - 1.01107$	0.999

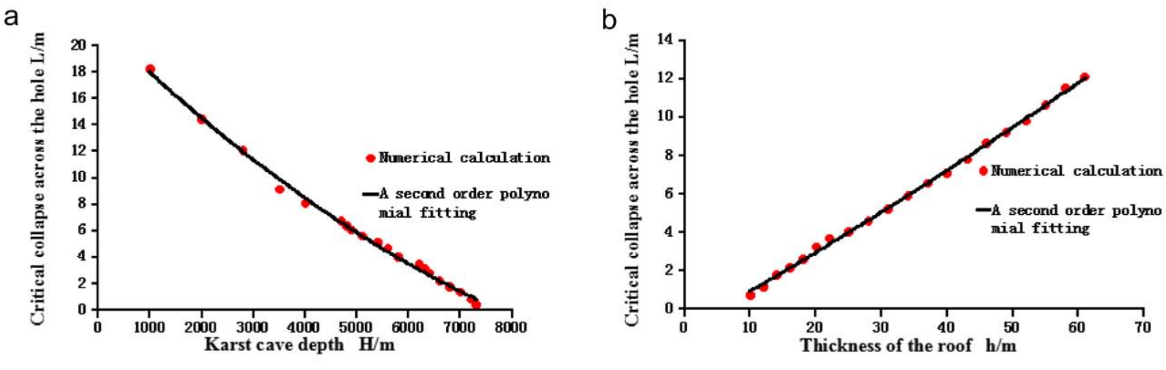

Fig. (5). Fitting curve of critical collapse cave span to factors in rectangle cave.

On the basis of Table **2** and Fig. (**5**), good quadratic function relationship exists between critical collapse depth and roof thickness, tunnel span and coefficient of horizontal pressure. The correlation coefficient is up to 0.99 with high fitting precision. Therefore, second-order polynomial function can well describe the changing relationship between critical collapse cave span and roof thickness or buried depth.

2.4. Prediction Formula of the Critical Collapse Cave Span Affected by Multi-Factor

The real fracture-cavity oil fields are usually under the influence of many factors, whereas the previous analysis has prediction formula of the critical collapse cave span affected by single factor. In order to analyze the combined effect of roof thickness and buried depth on collapse cave span, multivariate regression analysis method is used to establish the prediction formula of the critical collapse cave span affected by multi-factor.

Table **2** shows a good quadratic function relationship between the critical collapse cave span and the single factors including roof thickness *h* and buried depth *H*. Therefore, when considering the prediction formula of the critical collapse cave span affected by multi-factor, we can assumed the function between the critical collapse cave span *L* and the roof thickness *h* or buried depth *H* as follows:

$$L=AH^2+BH+Ch^2+Dh+E$$

In which A, B, C, D, and E are undetermined coefficients.

Table **3** lists the calculation results of critical collapse cave span changing with roof thickness and buried depth.

Table 3. The calculation results of critical collapse cave span under different depths and roof thicknesses.

h (m)	H (m)	L (m)	h (m)	H (m)	L (m)	h (m)	H (m)	L (m)	h (m)	H (m)	L (m)
25	7300	0.4	10	5800	0.8	25	5400	5.1	34	5800	5.9
25	7200	0.8	12	5800	1.2	25	5100	5.6	37	5800	6.6
25	7000	1.4	14	5800	1.8	25	4900	6.1	40	5800	7.1
25	6800	1.8	16	5800	2.2	25	4800	6.4	43	5800	7.8
25	6600	2.2	18	5800	2.6	25	4700	6.8	46	5800	8.7
25	6400	2.8	20	5800	3.3	25	4000	8.1	49	5800	9.2
25	6300	3.1	22	5800	3.7	25	3500	9.2	52	5800	9.8
25	6200	3.5	25	5800	4.1	25	2800	12.1	55	5800	10.7
25	5800	4.1	28	5800	4.6	25	2000	14.5	58	5800	11.5
25	5600	4.7	31	5800	5.2	25	1000	18.3	61	5800	12.1

According to the numerical calculation results of Eq.(1) and Table **3**, the undetermined coefficients A, B, C, D, and E can be determined by multiple regression analysis, and the prediction formula of the critical collapse cave span is as follow:

$$L=1.323\times10^{-7}H^2-0.0038H+0.0004395h^2+0.187h+16.67...$$

The correlation coefficient of Eq. (2) is 0.98, indicating it's high accuracy.

CONCLUSION

This work proposed a method of span dichotomy reduction to determine the critical collapse cave span. Following conclusions are drawn:

(1) Prediction formula of collapse cave span is determined by numerical calculation quantitatively, indicating that vertical shear stress leads to the collapse and failure of the cave.

(2) The critical collapse cave span decreases with the increase of buried depth, but enlarges with the increase of roof depth.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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