Stress Distribution and Fracture Development Potential in Rocks around Karst Caves in Carbonate Reservoirs

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Abstract. Karst holes and caves are well developed due to karstification in carbonate reservoirs. Stress distribution and fracture development around karst caves are of great significance to evaluate the storage and migration of hydrocarbons in carbonate reservoirs. In this study, the stress distribution and fracture development of Ordovician buried hills in Jizhong depression in northern China were investigated. The rock mechanical parameters of the target area were determined based on logging data and the boundary loads of the target region were also determined. Next, a numerical stress-analysis model was developed to investigate stress around the karst caves in Jizhong depression. Fracture development in the surrounding rocks of the karst caves was also analyzed. Results show that the principle vertical, maximum horizontal, and minimum horizontal stresses of studied area are all compressive with an approximate value of 100 MPa, indicating that the caves are under a stress environment in which mainly the top and lateral sides of caves bear pressure. The stress in the surrounding areas of the caves are quite homogeneous, and the fracture development index in these areas is low, making it difficult to form pathways for oil and gas migration. However, the stress near the top of the caves is relatively larger and the fracture development index is relatively higher, so that the rocks in this area tend to fracture and form...
migration pathways. This study is expected to provide scientific basis for the exploitation and development of oil and gas from the carbonate reservoirs in Jizhong depression.

1. Introduction

In carbonate reservoirs, different sizes of karst holes or caves usually develop as a result of karstification. These holes and caves are important for the storage and migration of oil and gas in the reservoirs [1]. In recent years, many researchers have studied the stress distribution around the karst caves in carbonate reservoirs. Wang [2] proposed a method to synthetically identify karst-cave reservoirs. Xiao [3] studied the characteristics of karst-cave reservoirs. Jin [4] developed a genetic model for karst-cave reservoirs in buried hill. However, there is still a lack of studies on stress distribution and fracture development around karst caves in carbonate reservoirs, which strongly affect the storage and migration of oil and gas in the reservoirs. To this end, this study took the Ordovician carbonate reservoirs in Jizhong Depression as an example to study the stress distribution in the surrounding rocks of karst caves with semicircle and elliptic shapes.

2. Determination of Rock Mechanical Parameters

Fault blocks are greatly developed in the bottom of Central Hebei Depression due to the crust extrusion since the tertiary period. The movement of these fault blocks and bore weathering resulted in buried hills in these areas. From the beginning of Eocene Epoch to the early stage of Oligocene, the movement of Renxi fault was very frequent, resulting in significant structure deformation and filling effect in Central Hebei Depression. Fractures and karst caves are extensively developed in the buried hills [5].

The relationship between rock mechanical properties and rock acoustic parameters have been well established [6]. On this basis, the rock mechanical properties can be calculated from acoustic logging data. The dynamic elastic modulus and dynamic Poisson’s ratio of the rock can be obtained as follows.

\[
E_d = \frac{\rho(3\Delta t_s^2 - 4\Delta t_p^2)}{\Delta t_s^2(\Delta t_s^2 - \Delta t_p^2)} \quad (1)
\]

\[
\mu_d = \frac{1}{2}\frac{\Delta t_s^2 - 2\Delta t_p^2}{\Delta t_s^2 - \Delta t_p^2} \quad (2)
\]

Where \(E_d\) is the dynamic elastic modulus of the rock, MPa; \(\mu_d\) is the dynamic Poisson’s ratio of the rock, dimensionless; \(\Delta t_s\) and \(\Delta t_p\) are the time differences of S wave and P wave, respectively, s/m; \(\rho\) is the density of the rock, kg/m^3.

Because numerical simulation is a static process, the static values of elastic modulus and Poisson’s ratio of the rock are needed for the simulation. So the above dynamic parameters should be converted
to static values. Based on existing achievements [6], the static rock mechanical parameters can be obtained using the following equations.

\[
\begin{align*}
E_s &= 0.2526 + 0.7095 E_d \\
\mu_s &= 0.2168 + 0.2500 \mu_d
\end{align*}
\]

Where \( E_d \) is the static elastic modulus of the rock, MPa; \( \mu_d \) is the static Poisson’s ratio of the rock, dimensionless.

Two independent mechanical parameters, static elastic modulus and Poisson ratio, can therefore be obtained by Eqs. 1-3. Other mechanical parameters of rock, such as tensile strength, compressive strength and shear strength, are found related to static elastic modulus and/or Poisson ratio, and therefore, they can be determined using these two parameters.

In this work, a well section of 3620 - 3700 m of Ren NO.76 Well in the studied area was investigated. The mechanical parameters of three rock layers were calculated using the above formulas. The average mechanical parameters of the three layers were regarded as those of the studied area, which are reported in Table 1.

| Depth (m) | Ed (MPa) | Ed (MPa) | Es (MPa) | Sc (MPa) | St (MPa) | Ss (MPa) | Φ (°) | σv (MPa) | σH (MPa) | σh (MPa) |
|----------|----------|----------|----------|----------|----------|----------|-------|----------|----------|----------|
| 3620     | 57945    | 0.44     | 41365    | 177.02   | 11.91    | 19.2     | 105.47 | 108.35   | 97.44    |
| 3660     | 60547    | 0.45     | 43211    | 166.63   | 13.89    | 19.3     | 105.66 | 108.88   | 98.03    |
| 3700     | 61386    | 0.49     | 43806    | 160.62   | 13.38    | 19.3     | 107.47 | 109.89   | 99.03    |
| AVG      | 59959    | 0.46     | 42794    | 168.09   | 14.01    | 19.2     | 106.50 | 109.04   | 98.17    |

where Ed and Es are dynamic and static elastic modulus, respectively; \( \mu_d \) and \( \mu_s \) are dynamic and static Poisson’s ratio, respectively; Sc, St and Ss denote compressive strength, tensile strength, and shear strength, respectively; \( \Phi \) is the internal friction angle; \( \sigma_v \), \( \sigma_H \) and \( \sigma_h \) are the principle vertical, maximum horizontal and minimum horizontal stress, respectively; AVE is the abbreviation of average.

3. Stress Analysis of Karst Caves

Due to the growth of faults and the long-term effect of groundwater dissolution, karst caves extensively developed in deep formations of Jizhong Depression. Yu and Li studied hole enlargement caused by karst caves in buried-hill carbonate reservoirs in this area and found the maximum enlargement value of 36.76 cm and vertical height of 5.6 m. It is difficult to determine the real stress state in the surrounding rock of karst caves because of the complicated stress environment around these caves. A semicircular karst cave model was first developed in this work. The development of this model and the analysis results are introduced in detail in this section. Next, similar approach was applied to the study of elliptical karst caves.
3.1. Stress around an elliptical cave

Stress distributions around an elliptic karst cave under three types of loading conditions were obtained from numerical simulations, as presented in Fig. 1.

![Stress distribution](image)

**Figure 1.** Stress distribution around an elliptic karst cave under (a) lateral load only, (b) vertical load only, and (c) both lateral and vertical loads.

As shown in Fig. 1a, when the horizontal crustal stress dominates the region, the maximum compressive stress occurs on the top and bottom areas of karst cave ranging from 109 to 125 MPa. While the stress at two sides of the cave has the minimum value ranging between 50 and 60 MPa.

Fig. 1b shows that the stress is within the range of 25 - 60 MPa for the condition with vertical load only. Compared with the lateral-loading case in Fig. 1a, the stress values in this case are about half of those in Fig. 1a. The minimum compressive stress appears at the top and bottom of the cave, and the stress at both sides of cave is relatively larger in compression than other areas.

Fig. 1c displays that the maximum compressive stress, ranging between 85 and 102 MPa, appears in the top area of the elliptic karst cave and the stress concentration effect is obvious in this load situation. In other areas, the stress are relatively smaller, especially at both sides of cave.

3.2. Fracture analysis in the surrounding rocks of an elliptical cave

Under the lateral load condition (Fig. 1a), the average shear fracture rate and average tensile fracture rate in the top area of the karst cave are 1.297 and 1.236, respectively; and the average fracture development index of this area is 1.254. Therefore, the top area of the karst cave belongs to fracture development area. Similarly, the fracture development index of the bottom area is determined to be 0.835, indicating this area belongs to fracture development area as well.

Fig. 1b shows that under the vertical load condition, the stress at the top and bottom area of the cave is relatively smaller, while the stress at both sides of the cave is relatively larger with a fracture development index of 0.831, which indicates this area is also fracture development area.

Fig. 1c displays that under both vertical and lateral loads, the maximum principle stress on the top of the karst cave is larger compared with other areas due to locally strong stress concentration. The shear fracture rate and tensile fracture rate of this area are 1.366 and 0.919, respectively; and the fracture
development index is 1.053, indicating that this area is fracture development area. Meanwhile, the stress at two sides of the karst cave is smaller than that of top area and the fracture development index is 0.338, indicating this area is free of fracture development.

4. Conclusions
(1) For an elliptic karst cave under lateral compression only, the stress at the top and bottom areas of karst cave is the maximum and these areas are fracture development area under lateral compression. For an elliptic karst cave under vertical compression only, the stress at both sides of the cave is relatively larger compared with that at the top and bottom area of the cave, while the stress value of the entire model is small, resulting in low fracture development index. For an elliptic karst cave under both vertical and lateral compression, the stress at the top area of the cave presents maximum value and the fracture development index in this area is high.

(2) The vertical, maximum horizontal, and minimum horizontal principle stresses of the studied area are all compressive with an approximate value of 100 MPa, indicating that the caves in carbonate reservoirs are in a stress environment in which both top and lateral sides of caves bear pressure. When the cave has an elliptical shape, the top areas of the cave present relatively larger stress value and fracture development indices, indicating fractures and migration pathways are likely to develop in these areas.

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