Study on the Fatigue Failure Law of Gas Storage Caprock Under Periodic Injection and Production

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Abstract. Whether qualitative or quantitative, whether macroscopic or microscopic, Predecessors' research on the sealing ability of caprocks is concentrated on the static model of the caprock. A few scholars have also proposed the sealability evaluations of the caprock dynamic evolution process, they are all aimed at the dynamic evolution of geological historical periods, and there are few studies on the sealability of gas storage caprocks under periodic injection and production. In this paper, the characteristics of stress and strain under alternating loads of rock and non-rock materials are investigated and experimentally studied to clarify the law of fatigue failure of gas storage caprocks under periodic injection-production. The results show that it is possible that the microcracks may develop and propagate in the rock after the gas storage has experienced many periodic injections and productions, when the stress is far less than the rock strength limit, And then a macroscopic deformation is formed. The accumulated plastic deformation of the rock will increase, and the plastic deformation rate will gradually decrease, as the number of injection and production increases.

1 Introduction

For gas storage, the caprock's plugging capacity refers to the ability of the gas storage to prevent natural gas from escaping, and it controls the vertical distribution, abundance and working pressure of natural gas in the gas storage. Taking the capillary sealing mechanism and hydraulic sealing mechanism of caprocks proposed by Watts in the United States in 1987 as a symbol [1], the sealing mechanism of caprocks and faults was systematically studied and qualitatively evaluated. Downey pointed out that the study of caprocks should be carried out from both macroscopic and microscopic aspects [2]; Grunau pointed out for the first time that evaporites such as gypsum and dolomite and shale are all effective caprocks [3], depositional environment, diffusion Speed, fracture formation and evolution are important parameters for evaluating caprocks. In 1996, Lu Yanfang and others proposed the overpressure sealing mechanism and the hydrocarbon concentration sealing mechanism [4], and established corresponding displacement pressure, effective stress and tensile strength, abnormal pore fluid pressure and diffusion coefficient according to different sealing mechanisms. The method of evaluating the sealing capacity, on this basis, establishes the industry standard for the evaluation of the sealing capacity of the caprock based on the macroscopic development characteristics and the microscopic sealing capacity of the caprock. The book "Research on Oil and Gas Reservoir Sealing" published by Lv Yanfang established a quantitative evaluation method for the sealing capacity of the caprock[4], and proposed the idea of evaluating the integrity of the caprock for the first time, and pointed out that the integrity of the caprock was damaged. The factors are structural fracture and hydraulic fracture[5-8]. Gradually realized that the petrological characteristics of the cap rock itself, especially the brittle-ductile characteristics, are the key factors that determine the integrity of the cap rock. Based on the density-strain, BRI and OCR [9], Byerlee friction law and Goetze's criterion, a quantitative judgment is proposed. Evaluation criteria for brittle-ductile transition of shale and gypsum [10]. Regardless of qualitative or quantitative caprock evaluation, predecessors paid more attention to the static evaluation method of caprock. Jin Zhijun proposed its sealing ability evaluation method for the dynamic evolution process of shale caprock [10].

Scholars generally believe that the study of the dynamic sealability of gas reservoir caprocks needs to be comprehensively evaluated from the macroscopic rock mechanics integrity and the microscopic capillary force sealability [11]. (1) The macro sealing ability depends on the lithology, thickness and the continuity of the lateral distribution of the cap layer; (2) the micro sealing ability depends on the permeability, porosity, permeability, specific surface and displacement pressure of the cap layer.

You Xiuling established the relationship between rock porosity, particle size median radius, burial depth and breakthrough pressure, and proposed a quantitative evaluation method that combines the macro and micro

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levels [12]. Fu Guang et al. divided the levels according to the size of influence through the micro and macro aspects, and discussed the method of comprehensively evaluating the sealing ability of the cap layer itself [13]. Scholars such as Sun Mingliang calculated the lithology, thickness and displacement pressure of the caprocks of more than 40 gas reservoirs in my country, and established the evaluation criteria for the caprocks of medium and high-efficiency gas reservoirs [14]. Zhang Lihan and Zhou Guangsheng calculated the actual data of 46 large and medium-sized gas fields in my country, and clarified the controlling factors that affect the sealing capacity of the gas reservoir caprock: the thickness of the caprock, fracture, displacement pressure and other influencing factors, and proposed the caprock Evaluation method of sealing ability [15]. Fan Ming et al. combed through the relationship between specific surface area, displacement pressure and caprock sealability, and proposed a comprehensive evaluation plan for the specific surface area and displacement pressure to judge the sealability of mudstone caprock [16].

However, for gas storage, previous studies on the sealing capacity of the cap rock, whether qualitatively or quantitatively, whether macroscopic or microscopic, are concentrated on the static model of the cap rock, and a few scholars have also proposed it. The evaluation of the sealing ability of the caprock dynamic evolution process is all based on the dynamic evolution of the geological history period. There are few studies on the sealing capability of the gas storage caprock under the action of periodic injection and production. Different from the development of conventional gas reservoirs, gas storages built from depleted oil and gas reservoirs require strong injection and production. The cap rock pressure is subject to periodic changes and changes frequently. The formation of microscopic rock fissures is the cause of the gas reservoir cap rock. The root cause of the failure [17].

2 Mechanical mechanism of rock failure under static action

The caprock lithology includes shale, dolomite and gypsum rock. Its brittleness and failure mechanism can be described by the method of full stress-strain characteristics. The peak strain can indicate the difficulty of rock failure. For mudstone caprocks, The brittleness of the rock is related to the slope and residual stress in the second half of the curve peak [17].

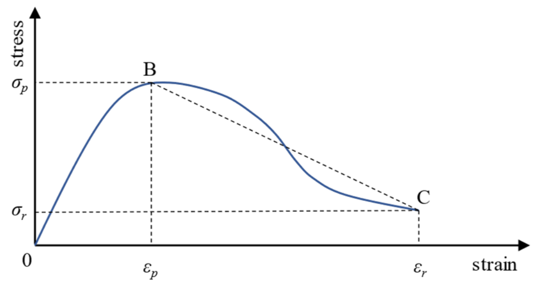

Fig.1 Model diagram of stress-strain curve of mudstone caprock

In the formula, point B corresponds to the peak stress, point C corresponds to the residual stress, and, are the peak stress and the residual stress, respectively;, are the peak strain and the residual strain, respectively.

The calculation formula of using rock brittleness index to describe the curve shape of cap rock at the back of the peak is:

$$I_1 = \frac{\sigma_p - \sigma_r}{\sigma_p} \tag{1}$$

$$I_2 = \frac{\varepsilon_r - \varepsilon_p - \varepsilon_{\max r-p}}{\varepsilon_{\min r-p} - \varepsilon_{\max r-p}} \tag{2}$$

$$BRIT = I_1\omega + I_2(1-\omega) \tag{3}$$

In the formula, are the peak stress and the residual stress, respectively;, are the peak strain and the residual strain, respectively; is the minimum peak strain minus the residual strain, is the maximum peak strain minus the residual strain, and ω is the relative weight. Through experiments, we can initially understand the mechanical mechanism of rock failure under static action of the caprock.

3 Mechanical mechanism of rock failure under dynamic action

By referring to the strain characteristics of non-rock materials under the action of periodic alternating stress, we can understand the stress-strain curve mode of the rock under the action of cyclic stress. In the first stage, after starting to load the stress, the curve from the initial residual stress point A should have been extended along the elastic loading line (the dotted line in the figure), but the actual situation has shifted; in the second stage, after the unloading starts, The unloading line should be parallel to the loading line, but the actual unloading line did not deviate along the elastic unloading line (the dotted line in the figure), thus forming a hysteresis loop; in the third stage, repeated loading and unloading is sufficient After more times, the hysteresis loop gradually stabilizes [18].

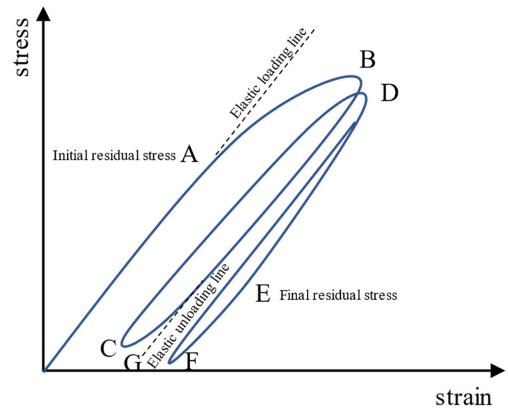

Fig.2. Stress-strain curve model diagram under cyclic stress

Applying periodic alternating stress to the sandstone, the hysteresis loop gradually shifts toward the direction of increasing strain, and the shape closure of the hysteresis loop is getting higher and higher, revealing that the plastic deformation of the rock becomes larger, but the plastic deformation rate is gradually reduced [19]. For sandstone gas storages, reservoirs and faults will increase the risk of local plastic deformation after a period of intense injection and production.

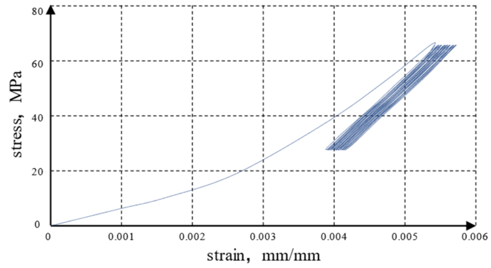

Fig.3. Typical stress-strain hysteresis curve of sandstone

Similar to the change of the stress-strain curve of sandstone, the hysteretic loop of mudstone gradually shifts toward the direction of increasing strain, and the shape closure of the hysteretic loop is getting higher and higher, revealing two points: 1. With the number of cycles Increasing, the cumulative plastic deformation increases, but the rate of plastic deformation decreases; 2. During the cycle of loading and unloading, the damping ratio of mudstone finally converges to a fixed value. In addition, as the number of cycles increases, the dynamic elastic modulus of mudstone gradually increases and eventually tends to converge[20].

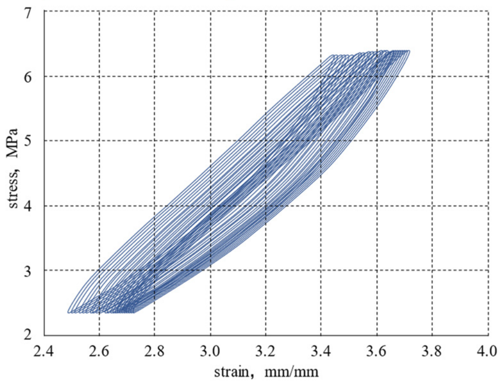

Fig.4. Typical stress-strain hysteresis curve of mudstone

4 Fatigue failure of rock

The in-situ stress field of gas storage also changes periodically with the change of periodic injection and production. In addition to different degrees of elasto-plastic deformation, it may also cause local stress concentration. This stress concentration will cause the rock to accumulate and form fatigue damage[21].

Therefore, under the action of cyclic loading, from a microscopic point of view, we should not only consider the creep of the rock, but also the possibility of fatigue damage to the rock [22]. "Fatigue failure" refers to the phenomenon that structural failure occurs after a certain number of cycles, far from reaching the strength limit.

Periodic disturbance stress is the external cause of fatigue and a necessary condition for fatigue. Fatigue failure occurs at a certain point in the rock. Fatigue failure starts from somewhere with higher stress. Once the microscopic deformation of the structure begins to accumulate, it will eventually lead to fatigue failure. There are many differences between static damage and fatigue damage. Periodic injection and mining are easy to cause fatigue damage: 1. Static damage is the instantaneous damage produced when the stress reaches the strength limit. Fatigue damage is one In the long-term process, under the action of cycles, after the accumulation of long-term stress, micro-cracks are generated locally from the fatigue source and gradually expand outward; 2. The condition for static failure is to reach the strength limit, but fatigue failure does not need to reach The strength limit is likely to occur, because the stress can gradually accumulate under the action of cycles [24]; 3. Due to the different triggering mechanism, the fractures of the two are also different. The fracture of fatigue damage can be seen in a flat picture, mainly It is caused by repeated squeezing and relaxation, and repeated friction, which is also an important sign to distinguish static failure from fatigue failure; 4. From the perspective of determinants, fatigue failure is not only related to the nature of the rock itself, but also It is related to external factors such as rock burial depth, fluid charging, fluid properties, and fracture development degree.

5 Conclusion

(1) Under static action, the difficulty of damage to the mudstone caprock of a gas storage can be expressed by the magnitude of the peak strain, and the magnitude of its brittleness is related to the slope and residual stress in the second half of the curve peak.

(2) After multiple rounds of injection and production in the gas storage, it is possible that microcracks may develop and propagate in the rock when the stress is far less than the rock strength limit. After the occurrence of microcracks, continuous periodic injection and mining will gradually accumulate the damage amount, and after accumulation to a certain extent, it will eventually show up as a macroscopic plastic deformation.

(3) When the injection-production intensity remains unchanged, the increase in the number of cycles will increase the accumulated rock plastic deformation, but the plastic deformation rate will gradually decrease.

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