Development and application of triaxial rock shear - self-supporting fracture conductivity experiment system

XIU Nailing¹², YAN Yuzhong¹², Wang Xin¹², Cai Bo¹², Liang Tiancheng¹², Fu Haifeng¹²

¹ Petrochina Research Institute of Petroleum exploration & Development, Beijing, 100083, China
² Key Laboratory of Reservoir Stimulation-CNPC, Langfang, Hebei, 065007, China
xiunailing69@petrochina.com.cn

Abstract. The structure and function of shear - self-supporting fracture conductivity test device in great detail were presented. This device system consists of five parts: vertical loading system, horizontal shear loading system, the servo control system, power system, shear box and its sealing system, digital control and acquisition system. It can provide vertical force up to 2000KN, shear force 500KN, lateral stress 50MPa and hydraulic pressure 40 MPa. Characteristics of the system are illustrated as follows. (1) The experimental research of rock shear failure can be performed under three axial stress conditions, the lateral stress is loaded by hydraulic oil and the vertical stress is loaded by pressing machine. (2) True triaxial and quasi-triaxial loading modes can be switched by using different sealing sleeves. (3) The shear seepage coupling and self-supporting fracture conductivity tests could be conducted under three axial stress conditions. (4) The stress and displacement loading modes under different loading rate can be realized by servo system. Based on this experimental system, shear-fracture conductivity test under three axial stress conditions was performed on shale specimen and its reliability was verified. The experimental system can be used to provide theoretical basis for the shear destruction mechanism and Self-supporting shear fracture conductivity test under true triaxial stress conditions. The research has an important guiding significance on the formation mechanism of unconventional reservoir shear fracture and the flow capacity of self-supporting shear fracture and its influencing factors.

Keywords: Shear fracture, Self-supporting fracture, fracture conductivity

1. Introduction
With the development of unconventional reservoirs such as shale gas, hydraulic fracturing plays an increasingly important role in ensuring the economic and effective development of unconventional reservoirs [1-2]. Unconventional oil and gas reservoirs often use slick water large-scale fracturing technology in order to form a large-scale fracture network and increase the reservoir reconstruction volume (SRV). Natural fractures in shale reservoirs are developed, and the fracture network formed by fracturing contains a large number of shear-slip fractures[3-5]. Shear-slip fractures on the fracture surface can promote the bulge of rough fractures to support the fractures. After the fractures of the proppant are closed, residual fractures can still be formed, and this self-supporting effect has an important influence on the effect of reservoir stimulation. Therefore, in-depth study of the conductivity of self-supporting shear fractures under reservoir stress is very important for evaluating the effect of reservoir reconstruction and reasonable production allocation. Some progress has been made in the development of shear seepage equipment at home and abroad [6-16], but there are still some
shortcomings, such as low seepage pressure, which cannot meet the experimental requirements of high seepage pressure, and the relationship between conductivity of self-supporting shear fractures and shear displacement and stress. Not enough research. To this end, the PetroChina Exploration and Development Research Institute has developed a high-stress, high-permeability true triaxial shale shear-seepage experiment system. The development of this system can provide an experimental basis for simulating the reservoir shear failure mechanism and self-supporting shear fracture conductivity-stress coupling simulation under true triaxial stress conditions, and for the evaluation and research of self-supporting shear fracture conductivity. The law of fluid flow in shear fractures provides a basis.

2. Basic composition of the experimental system

The true triaxial shear-self-supporting crack diversion experiment device is mainly composed of five parts: vertical loading system, horizontal shear loading system, hydraulic servo loading system, shear box and its sealing system, and digital control and acquisition system. The overall physical map of the device is shown in Figure 1.

![Figure 1. True triaxial shear- self-supporting fracture conductivity test system](image)

2.1. Vertical loading system

The function of the vertical loading system is to apply vertical compressive stress to the rock sample, which is composed of the main frame, loading cylinder, force sensor, displacement sensor, controller and other parts, as shown in the figure. Among them, the main frame adopts an integral casting design to ensure sufficient rigidity; the loading cylinder is installed on the beam of the main frame, the piston downwardly applies axial load to the sample, the force sensor and the displacement sensor detect the axial force and the axial piston displacement. The controller adopts the EDC all-digital servo measuring and controlling device (EDC220V) originally imported from Germany DOLI Company, which controls the axial load in real time through the computer, and realizes the microcomputer servo closed-loop control according to the program segment or the set value. In the stress control mode, the dilatancy at constant stress can be measured; in the displacement control mode, the stiffness of the specimen can be controlled and sheared.

2.2. Horizontal shear loading system

The function of the horizontal shear loading system is to apply horizontal shear stress to the rock sample to complete the shear test of the sample. As shown in the figure, the system is mainly composed of shear frame, loading cylinder, force sensor, displacement sensor, controller and other parts. The shearing frame is also made of integral casting to ensure sufficient rigidity; rollers are installed under the frame, and the indenter is in close contact with the upper and lower shearing boxes during the rolling and shearing process on the vertical frame guide rail, and there is no turning force, and the force is even. The loading cylinder is installed on the rear beam of the shear frame; the force sensor and the displacement sensor detect the shear force and the piston displacement respectively.

2.3. Hydraulic servo loading system

The confining pressure and seepage loading device are controlled by two independent servo controllers, which are respectively controlled by AC servo motor and AC servo motor controller, reducer, ball screw, transmission system, pressurized water tank (using stainless steel material), and fuel tank, Pressure sensor, three-way hand valve, etc. The cylinder adopts a combined seal, small
friction, volume change measurement, and high force value control accuracy; the frame material is made of high-quality carbon steel, and the screw is high-precision ball screw; The frame material is made of high-quality carbon steel, the volume change measurement, and the force value control precision is high.

2.4. Shear box and sealing system
The shear box and its sealing system are the core design of the true triaxial shale shear-seepage test device, which has been authorized as a utility model patent (ZL 201520425463.2). In the past, shear seepage equipment mostly used the combination of upper and lower shear boxes and sealing systems. The upper and lower shear box bodies of the shear box developed by Xu Jiang et al. [9] are made of stainless steel, and the sealing material is made of oil-resistant rubber and PTFE bronze composite material according to its location, and the test piece is installed under the condition of ensuring sealing. It is easier and more convenient, but the head to withstand is lower, only 5MPa. The shear box in this article is different from an open structure in which the general shear box is composed of upper and lower box bodies. It consists of the main body of the shear box, two glands, two shear pistons, up and down vertical loading pistons, and sealing rings. Close the cavity, as shown in Figure 2. The entire shear box is made of denser steel, which has the characteristics of high compressive strength and good water corrosion resistance. The main body is a permeable structure with an outer square and an inner circle. The upper and lower holes are equipped with vertical loading pistons to apply axial pressure to the rock sample. The left and right sides are sealed and compacted with two cylindrical glands; an integrated polyurethane sealing rubber sleeve. The wrapped rock sample is loaded in the middle of the main body of the shear box, the hydraulic oil passes through the hydraulic oil inlet and outlet on the back side of the main body of the shear box, and is poured into the confining pressure chamber outside the sealing sleeve to apply confining pressure; the split shear piston is the same as the gland. Between them is fixed with a positioning pin, and the central through hole of the shear piston is connected with the seepage fluid inlet and outlet on the gland to form a seepage channel to complete the shear seepage coupling test of the rock sample.

The polyurethane material itself has the characteristics of wear resistance, oil resistance, and aging resistance. The sealing of the shear box is mainly realized by an integrated polyurethane sealing rubber sleeve, as shown in Figure 3. The rock sample is in close contact with the sealant sleeve through the top sleeve and two pairs of friction plates. The upper and lower top sleeves are clamped into the upper and lower holes of the shear box body, and respectively abut the end faces of the upper and lower vertical loading pistons to realize the axis of the rock sample. Load towards the force; the rubber sleeves on the front and rear sides match the size of the rock sample. The circular end faces of the seal rubber sleeve on the left and right sides are completely inserted into the inner cavity of the main body of the shear box, and they are attached to the cavity wall to form a sealed cavity, which is full. The hydraulic oil can be loaded with lateral oil pressure; the rectangular grooves on the left and right sides are adapted to the size of the shearing piston, and the shearing force can be loaded by the external horizontal loading device. The shearing piston adopts a split structure, which is mainly composed of a top block made of high-density steel, a rectangular stop block, a cylindrical pin and a spring. The top block and the stop block are connected by a cylindrical pin with a spring to make the rock sample
After being cut, it can be pressed tightly on the rectangular top block to ensure the integrity of the shearing cracks.

2.5. Digital control and acquisition system
The digital control and acquisition system consists of a computer, various sensors and a Test control software system. Both the vertical loading device and the horizontal shear loading device have force sensors and displacement sensors to monitor and control force and displacement. The lateral direction adopts hydraulic soft loading, which is monitored and controlled by pressure sensors. The inlet of the shear box is connected to a constant speed pump to control the fluid flow. And there is a pressure sensor to monitor the inlet and outlet pressure changes during the experiment, which can accurately measure the flow rate and inlet and outlet pressure during the experiment.

3. The main functions and technical parameters of the experimental system

3.1. Main functions of the system
The true triaxial core shear-self-supporting fracture conductivity experimental device can complete the study of the influence of core mechanical properties and force characteristics on the conductivity of self-supporting fractures under the conditions of reservoir stress and fluid pressure. The main functions include:
(1) Conventional direct shear test to study the shear performance and failure laws of shale under different stress paths;
(2) Shear-conductivity coupling test to study the change law of shale shear fracture conductivity under different shear displacement and stress conditions;
(3) Self-supporting shear fracture conductivity damage test, to study the influence of different fracturing fluids on the conductivity of shale shear fractures in a simulated formation stress environment.

3.2. Main technical parameters of the system
The main frame of the true triaxial core shear-self-supporting fracture diversion experiment device adopts a monolithic frame structure, with an axial frame stiffness of 10GN/m and a horizontal frame stiffness of 5GN/m, which can meet the requirements. The axial direction can realize the smooth switching of force (stress), deformation (strain), displacement, and multiple control modes. The force range of the vertical loading part is 20-2000 kN and its force measurement resolution is 30 N; The force range of the horizontal shear loading part is 4-500 kN and its force measurement resolution is 20 N; The maximum lateral pressure of the hydraulic servo loading part is 50MPa, the maximum pressure of seepage fluid is 40MPa, the maximum rate of seepage fluid is 500 ml/min; The size of the square sample is 60 mm×60 mm×60 mm; The size of the cylindrical sample is φ25mm×50mm or φ100mm×200mm.

4. Shear-Self-supporting Fracture conductivity Coupling Test

4.1. Sample preparation
After the commissioning of the true triaxial core shear-self-supporting fracture diversion test device is completed, the Changqing sandstone outcrop is processed into a cube sample with a length, width and height of 60 mm. After the sample is processed and formed, the surface of the sample is polished again.
with a grinder, so that the flatness error of each end surface is controlled within 0.02mm. Then put the top sleeve, gasket I, gasket II, and rock samples into the polyurethane sealant sleeve in sequence, and seal with glue, as shown in Figure 4. Put the sealed sleeve with the sample in the shear box as a whole, and carry out the laboratory test.

Figure 4. The rock specimen in the seal sleeve

4.2. Experimental program
Investigate the influence of different normal stresses and different shear displacements on the conductivity of self-supporting shear fractures. The samples are divided into 2 groups. The normal and lateral stresses of group A are maintained at 10 MPa to test the changes in the conductivity of self-supporting shear fractures under different shear displacements; the shear displacements of group B remain unchanged, and the self-supporting shear displacements of group B are kept unchanged. Support changes in the conductivity of shear fractures.

| sample No. | Normal stress MPa | Lateral stress MPa | Shear displacement mm |
|------------|-------------------|--------------------|-----------------------|
| A1         | 10                | 10                 | 0.7, 1.5, 2.2, 3, 3.8 |
| A2         | 10                | 10                 | 1, 1.5, 2.2, 3, 3.8, 4.5 |
| A3         | 10                | 10                 | 0.3, 0.5, 0.7, 1, 1.25, 1.5 |
| B1         | 3, 10, 15         | 20, 25, 30         | 3, 10, 15, 20, 25, 30 |
| B2         | 2, 5, 10          | 15, 22, 30         | 2, 5, 10, 15, 22, 30 |
| B3         | 2, 7, 12, 18      | 23, 28, 32         | 2, 7, 12, 18, 23, 28, 32 |

4.3. Experimental results and analysis
The core undergoes shear failure in the shear box to form macroscopic fractures, and then the self-supporting shear fracture conductivity experiment is carried out. Figure 5 shows the self-supporting shear of three cores when the normal stress and lateral stress are unchanged. The fracture conductivity varies with shear displacement. It can be seen from the figure that when the shear displacement is small, the fracture conductivity increases with the increase of the shear displacement. As the shear continues, the conductivity tends to The reason is that in the initial stage of shearing, the process of replacing contact areas with voids created by the dilatancy effect is the primary factor that promotes the increase of fracture conductivity. As the shear displacement increases, the shear surfaces rub against each other. The roughness of the fracture surface decreases, and the fracture conductivity tends to be flat or slowly decreases. It can also be seen from the figure that the conductivity of different
samples can differ by an order of magnitude, which is mainly caused by the roughness of the shear fracture surface and the hardness of the core. Figure 6 is a curve of the conductivity of a self-supporting shear fracture with increasing normal stress under the condition that the shear displacement remains constant. It can be seen from the figure that the fracture conductivity is more sensitive to the normal stress. When the normal stress is relatively low, the shear fracture conductivity of different cores has a relatively large range of changes. As the normal stress increases, Fracture bulges gradually undergo compression deformation, and the flow channel gradually becomes smaller, resulting in a continuous reduction of fracture conductivity. Under high normal stress, the difference in fracture conductivity of different cores is decreasing.

![Figure 5. Curve of fractures conductivity changing with shear displacement](image1.png)

![Figure 6. Curve of fractures conductivity changing with normal stress](image2.png)

### 5. Conclusion

The structure and function of the core shear-self-supporting fracture conductivity test system are introduced. The experimental system has the following characteristics:

1. Servo control can be used to achieve high-precision measurement, with good reliability and practicability; it can achieve three-way stress loading, strong loading capacity, vertical loading capacity of 2000KN, shear loading capacity of 500KN, and lateral use of hydraulic soft loading, up to 50MPa, seepage pressure up to 40 MPa.

2. Through the unique loading method and sealing design of the shear box, the shear seepage experiment under triaxial stress can be realized. The sealing effect is good throughout the experiment, and the sample can be sheared to failure in the whole process. In the seepage coupling experiment, after shear failure, the conductivity experiment of self-supporting shear fractures under different shear displacements and different normal stresses can be continued.

3. Through preliminary experiments, the relationship curve between the shear stress and shear displacement of the sample under true triaxial stress was obtained; the self-supporting shear fracture conductivity experiment of shale was carried out, and the fracture conductivity under constant normal stress was obtained. The curve of capacity change with shear displacement and the change curve of fracture conductivity with normal stress when the shear displacement is constant. A preliminary display and analysis of each experimental data are carried out.

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