Stress-sensitivity analysis of rock mechanical and petrophysical properties of fractured tight sandstone under true-triaxial stresses in the laboratory

Jiaying Li¹,², Chunyan Qi¹,², Ye Gu¹,², Yu Ye², Jie Zhang³, Tuo Zhou²

¹ CNPC USA Corporation, Beijing, 100020, China
² CNPC Engineering Technology R&D Company Limited, Beijing, 102206, China
³ CNPC Tarim Oilfield, Korla, Xinjiang 841000, China

Abstract. In the process of oilfield production, effective stresses usually increase continuously and act as unequal triaxial stresses on the reservoir. However, most studies on rock stress sensitivity are conducted under conventional triaxial or uniaxial stress conditions, which cannot truly represent the in situ stress environment. In this work, two groups of fractured tight sandstones sampled from northwestern China were tested under true-triaxial stress environments to study the stress sensitivity of mechanical and petrophysical properties. The sandstones are elastically deformed under experimental stress conditions, showing an apparent correlation with fracture angles. The acoustic wave velocity increases linearly with the stresses, and the shear wave velocity is strongly affected by fracture angle and anisotropic effective stresses. The permeabilities decrease exponentially and show significant anisotropy with increasing effective stress, which is less stress sensitive when the fracture strike is parallel to the maximum horizontal principal stress than when it is perpendicular. This work successfully reveals the stress sensitivity of anisotropic permeability, stress-strain behavior, and acoustic wave velocity of fractured tight sandstone during reservoir depletion. The testing results provide an innovative method to accurately measure the anisotropic rock properties, offer new ideas about fractures identification, and have profound significance for exploration and development of tight reservoirs.

Introduction

As the remaining recoverable reserves of conventional resources are decreasing, unconventional resources, mainly tight oil and shale oil have gradually become the main force of the fossil energy supply in the last decade. A tight reservoir is usually characterized by high density, low permeability, high pore pressure, and natural fractures, as well as strong anisotropy and heterogeneity. Such reservoirs rely on stimulation technology to improve reservoir conductivity and productivity. The consequence of reservoir stimulation is basically influenced by rock mechanical and petrophysical properties, therefore, research into these issues is of important theoretical value and practical significance for the exploration and development of tight reservoirs. Extensive studies have indicated that rock mechanical and petrophysical properties are highly stress dependent¹-³, which means that the basic rock properties such as permeability, stress-strain behavior, and acoustic wave velocity would show strong anisotropy when in situ stresses change with reservoir depletion. However, most studies on rock stress sensitivity have been conducted under conventional triaxial or uniaxial stress conditions, which cannot truly represent the in situ stress environment and neglect the effect of the intermediate principal stress on rock properties. In this work, fractured tight sandstone from the Tarim Basin was tested under true-triaxial stresses in the laboratory based on a novel geophysical test apparatus, aiming to reveal the rock stress sensitivity of anisotropic permeability, stress-strain...
behavior, and acoustic wave velocity during reservoir depletion. This work comprehensively considered the influence of unequal in situ triaxial stresses and hydraulic fractures on mechanical and petrophysical properties of tight sandstone.

Rock stress-strain behavior can be used to understand rock deformation and failure mechanisms to guide reservoir evaluation and management. Initially, the stress-strain curves of only weak rocks could be obtained by simply increasing the stiffness of the loading system [4]. Later, servo control technology was developed to increase the overall stiffness of the testing system to obtain the stress-strain curves of hard rocks [5]. On this basis, a series of experiments was conducted to analyze rock stress-strain behavior by changing the direction and magnitude of applied stresses. Zong et al. [6] (2016) analyzed the stress-strain curve of sandstone under uniaxial compression, illustrating the volume dilatation properties in the loading process of sandstone. Xu et al. [7] (2011) described the energy transformation characteristics of the rock failure process under uniaxial and conventional triaxial stress conditions, which revealed the influence of the stress path on rock stress-strain behavior.

Acoustic wave velocity is regarded as a critical parameter for reservoir integrity assessments, internal defect detection, and fracture identification. Considering the influence of weak interfaces such as fractures, bedding, and joints, as well as the effect of unequal triaxial stresses, the evolution of acoustic wave velocity generally shows obvious anisotropy during oil and gas production. Many researchers have studied the anisotropy of compressional wave and shear wave velocities under triaxial or uniaxial stress conditions [8-12]. Vernik and Nur [10] (1992) analyzed the anisotropy of P-wave and S-wave velocities in shale, which was used to estimate shale maturation and fracture growth. Helmut et al. [11] (2002) and Zhang et al. [12] (2019) tested the seismic velocity of fractured rock. The results showed that the anisotropy of seismic velocity was closely related to fracture properties and stress states.

In oil and gas production, the pore pressure decreases and effective triaxial stresses increase continuously, resulting in permeability evolution. Accurate understanding of permeability evolution can improve the understanding of fluid migration patterns, long-term performance of production wells, and a reasonable fracturing program for a tight reservoir. However, conventional permeability is tested under uniaxial or conventional triaxial conditions where the intermediate and minimum principal stresses are equal ($\sigma_y = \sigma_\mu$) [13-15]. Recently, some experiments were attempted under in situ conditions [16-18]; however, such experiments are commonly conducted by vertically or horizontally drilling plugs and the results were limited by the plug sampling direction. This work successfully tested the stress-strain curves, anisotropic permeabilities, and acoustic wave velocities of deep fractured tight sandstones under true-triaxial stress environments and analyzed the stress sensitivity in different principal stress directions. Moreover, the sandstone samples are artificially fractured at different angles to simulate the fractures in the reservoir and compared with intact sample to evaluate the effect of those fractures.

**Experimental principles and methods**

**Sample preparation**

In this work, two groups (Group A and Group B) of sandstone samples were taken from the gas oilfield in the Kuqa depression of the Tarim Basin, where a Mesozoic–Cenozoic continental petroleum system developed. The reservoir is a typical ultra-deep fractured tight reservoir of mainly fine- to medium-grained sandstone with thinly interbedded mudstone and characterized by matrix permeability of 0.011–1.01 mD, porosity of 2.0%–7.8%, burial depth of 5000–7500 m, pore pressure of 116 MPa, and NEE—SWW thrust faults [19,20]. Each group consists of four sandstone samples of 80 mm × 80 mm × 80 mm, and three of them are artificially fractured with different angles (0°, 15°, and 30°), simulating natural and hydraulic fractures. In the process of the experiments, the strike of the artificial fractures is parallel to the minimum principal stress in sample Group A, and vice versa in Group B.
(Fig. 1). The samples are soaked in brine for 48 hours in a vacuum container to reach the water-saturated state. The chemical components of the brine are consistent with the formation water identified in the Tarim oilfield.

**Figure 1.** Sandstone samples (Sample A0/A1/A2/A3: fracture strike parallel to $\sigma_h$; sample B0/B1/B2/B3: fracture strike perpendicular to $\sigma_h$).

**Experimental procedure**

Equipped with an advanced geophysical imaging apparatus and gas–water seepage control device, the innovative true-triaxial geophysical testing system (Fig. 2) can create a true-triaxial stress environment and measure anisotropic permeability simultaneously. In addition, the equipment has acoustic emission sensors and ceramic piezoelectric sensors at each surface to monitor anisotropic wave velocity and fracture variations. This equipment can reach 1040 MPa of vertical stress, 520 MPa of horizontal stress, with 10 MPa of pore pressure and 200°C of testing temperature maximumly.

**Figure 2.** True-triaxial geophysical testing system (left); geophysical imaging cell (right).

The effective stress variations during reservoir depletion are determined by reservoir in situ stresses, the Biot coefficient, Poisson’s ratio, and pore pressure according to Biot’s poroelastic theory:[21]

$$\Delta \sigma = \alpha \cdot \frac{1-2\nu}{1-\nu} \cdot \Delta P_p, \sigma_e = \sigma_0 - \Delta \sigma = \sigma_0 - \alpha \cdot \frac{1-2\nu}{1-\nu} \cdot \Delta P_p$$

Where $\Delta \sigma$ is the variation of stress, $\sigma_0$ is the original stress, $\sigma_e$ is the effective stress, $\nu$ is the Poisson’s ratio, $\alpha$ is the Biot coefficient, and $\Delta P_p$ is the pore pressure variation.

The Biot coefficient and Poisson’s ratio of the reservoir are confirmed by laboratory experiments as 0.7 and 0.25, respectively. The initial in situ stresses $\sigma_v$, $\sigma_h$, and $\sigma_H$ of the research area are 159 MPa, 170 MPa, and 140 MPa, and the initial pore pressure is 116 MPa. The corresponding triaxial effective
stresses are calculated when the pore pressure decreases from 116 MPa to 36 MPa during reservoir depletion, where the effective vertical stress increases from 77.8 MPa to 133.8 MPa, maximum horizontal stress increases from 88.8 MPa to 107.5 MPa, and minimum horizontal stress increases from 58.8 MPa to 77.5 MPa. The stress loading path is designed as expressed in Table 1 and the loading rate is set as 0.0002 mm/s.

Table 1. Stress loading steps in the experimental process.

| loading step | Pore pressure (MPa) | In situ stresses (MPa) | Effective stresses (MPa) |
|--------------|---------------------|------------------------|-------------------------|
|              |                     | V          | H          | h          | V          | H          | h          |
| 1            | 116                 | 159        | 170        | 140        | 77.8       | 88.8       | 58.8       |
| 2            | 111                 | 159        | 167.7      | 137.7      | 81.3       | 90         | 60         |
| 3            | 106                 | 159        | 165.3      | 135.3      | 84.8       | 91.1       | 61.1       |
| 4            | 101                 | 159        | 163        | 133        | 88.3       | 92.3       | 62.3       |
| 5            | 96                  | 159        | 160.7      | 130.7      | 91.8       | 93.5       | 63.5       |
| 6            | 91                  | 159        | 158.3      | 128.3      | 95.3       | 94.6       | 64.6       |
| 7            | 86                  | 159        | 156        | 126        | 98.8       | 95.8       | 65.8       |
| 8            | 81                  | 159        | 153.7      | 123.7      | 102.3      | 96.9       | 67         |
| 9            | 76                  | 159        | 151.3      | 121.3      | 105.8      | 98.1       | 68.1       |
| 10           | 66                  | 159        | 146.7      | 116.7      | 112.8      | 100.5      | 70.5       |
| 11           | 56                  | 159        | 142        | 112        | 119.8      | 102.8      | 72.8       |
| 12           | 46                  | 159        | 137.3      | 107.3      | 126.8      | 105.1      | 75.1       |
| 13           | 36                  | 159        | 132.7      | 102.7      | 133.8      | 107.5      | 77.5       |

**Experimental principles**

(1) Calculation of acoustic wave velocities

The compression wave and shear wave velocities are calculated by:

\[ V_{p/s} = \frac{L}{\Delta t_{p/s}}, \Delta t_{p/s} = t_{total} - t_{p0/s0} - t_0 \]

Where \( V_{p/s} \) is the velocity of the compression waves (or shear waves); \( L \) is the length of the sample; \( \Delta t_{p/s} \) is the propagation time of the compression waves (or shear waves); \( t_{total} \) is the total time recorded by the system, which can be read directly from the source data; \( t_{p0/s0} \) is the propagation time of the compression waves (or shear waves) between the sensors without a sample, and \( t_0 \) is initial response time of the system, which is a fixed value that is related to the signal transmission of the test apparatus.

(2) Calculation of anisotropic permeability

The steady state method is adopted to measure the permeability of intact and fractured tight sandstone samples in each loading step. The flow rate and pressure difference show a linear relationship, which indicates that the fluid flow in the samples conforms to linear Darcy flow, and the permeability can be calculated by Darcy’s law:

\[ k = \frac{\mu Q L}{A \Delta P} \cdot 10^9 \]

Where \( Q \) is the injection rate, ml/s; \( \mu \) is the fluid viscosity, Pa·s; \( \sigma_e \) is the cross-sectional area, m²; \( k \) is the permeability, md; \( L \) is the length of the sample, m; and \( \Delta P \) is the pressure difference at inlet and outlet, MPa.

**Experimental results and discussion**

*Stress-strain behavior*
The stress-strain behavior of the intact and fractured samples is tested under different stress conditions (Fig. 3). The samples are initially in the stage of pore space compaction and then in the stage of approximately linear elastic deformation during stress loading. Irreversible inelastic strains exist in the intact and the fractured samples after stress unloading, and the irreversible strain of the fractured samples (0.007–0.009) was significantly larger than that of the intact samples (0.0025–0.0035), indicating that the fractures could promote rock deformation; additionally, the deformation moduli in the principal stress directions show obvious anisotropy.

The changes in intermediate principal strain and maximum principal strain are obviously greater than those of minimum principal strain when the minimum principal stress is parallel to the fracture strike, which is in accordance with the stress-strain behavior of the intact samples. However, when the minimum principal stress is vertical to the fracture strike, the intermediate principal strain gradually becomes larger than that of the minimum principal strain and approaches the value of the maximum principal strain with the increase of fracture angle (from 0° to 30°), illustrating that the stress-strain is highly dependent on fracture angle.

Figure 3. Combined stress-strain curves for the three principal stress axes up to loading and unloading step 13 (Sample A0/A1/A2/A3: fracture strike parallel to $\sigma_h$; sample B0/B1/B2/B3: fracture strike perpendicular to $\sigma_h$).

**Anisotropic permeability**

The anisotropic permeability of the intact samples and those with artificial fractures at different angles are measured at each loading step (Fig. 4). The permeability of the fractured samples (~10 mD) is one order of magnitude larger than that of the intact samples (~1 mD). With the increase of the effective stresses, the permeability of the intact samples decreases exponentially and shows apparent anisotropy because of the different deformation under the influence of the three unequal principal stresses ($\sigma_v$, $\sigma_h$, and $\sigma_H$). For the intact samples, $\sigma_h$ is the maximum principal stress from loading Step 1 to Step 6; correspondingly, the permeability in the direction of $\sigma_H$ is distinctly lower than that in the direction of $\sigma_v$ and $\sigma_h$. The vertical stress $\sigma_v$ becomes the maximum principal stress from step 7, and the permeability is still greater than that in the direction of $\sigma_H$, which demonstrates that the early stress environment can significantly affect the permeability variation during reservoir depletion. In addition, the permeabilities in $\sigma_v$ and $\sigma_h$ show little difference during the whole loading process though the stress values in these two directions differ greatly, which probably resulted from microfractures of the rock skeleton induced by rock deformation. The solid particles generated in the process of microfracturing enter the pore throats in the directions of $\sigma_v$ and $\sigma_h$ and effectively improve the stiffness of the pore throats to a certain extent and inhibit further closure.
For the fractured samples, $k_v > k_h > k_H$ when the fracture strike is parallel to $\sigma_h$ and the fracture angle $\beta = 0^\circ$; $k_v \approx k_h > k_H$ when $\beta = 15^\circ$; and $k_h > k_v > k_H$ when $\beta = 30^\circ$. The permeability in the $\sigma_v$ direction is obviously dependent on the fracture angle, which indicates that the flow resistance of oil and gas increases in the fracture along the $\sigma_v$ direction with the change of fracture angle. However, the flow path in the $\sigma_h$ direction is parallel to the fracture strike and would not change with the fracture angle. Therefore, the permeability in the $\sigma_v$ direction becomes gradually less than that in the $\sigma_h$ direction. The direction of $\sigma_H$ intersects with the fracture plane, and the permeability is always minimum. When the fracture strike is perpendicular to $\sigma_h$, $k_v$ and $k_H$ are close when $\beta = 0^\circ$ and $15^\circ$; $k_H > k_v > k_h$ when $\beta = 30^\circ$. The permeability $k_h$ decreases smoothly, while $k_v$ and $k_H$ show obvious fluctuations with increasing stress, which resulted from: a) microslip of the fracture interface induced under the combination of external loading and penetrating force and random (or periodic) stress releases at the interface, resulting in fluctuations of permeability; and b) the deformations of the fracture surface and of the matrix are inharmonious under the Poisson effect, leading to the shedding and migration of interfacial particles and the change of fracture aperture.

![Figure 4. Permeability along the three principal stress directions with stress loading steps (Sample A0/A1/A2/A3: fracture strike parallel to $\sigma_h$; sample B0/B1/B2/B3: fracture strike perpendicular to $\sigma_h$).](image)

**Acoustic wave velocity**

The variations of acoustic wave velocity with stress loading step are showed in Figures 5 and 6 for Group A and Group B, respectively. Because of the different propagation mechanisms of P-waves and S-waves, the responses of the P-waves and S-waves to fracture occurrence and fracture angle are distinct. The P-waves velocity increases linearly and monotonically with the increase of stress loading. The velocity in the direction of $\sigma_H$ is greater than that in the direction of $\sigma_h$, indicating that rock is compressed with the increase of external stresses and the internal pores and fractures are gradually closed, contributing to the increase of P-waves velocity. In the process of stress unloading, the velocities of P-waves and S-waves are both larger than that in the corresponding stress loading stage, but the values are numerically approximate, which indicates that the samples mainly remain under recoverable elastic deformation throughout the experiments.

The velocity of S-waves ($2.3–2.6$ km s$^{-1}$) increases linearly with the stress loading and is apparently lower than P-waves velocity ($3.8–4.1$ km s$^{-1}$). The sensitivity of S-waves to external stress is stronger than that of P-waves, and the velocity of S-waves shows obvious anisotropy during stress loading. The velocity of shear wave S1 is larger than that of S2, which is because of the stronger compaction in the $\sigma_H - \sigma_v$ plane. Moreover, fractures could greatly affect S-waves propagation. The velocity of S1-waves has weak correlation with the fracture angle, while the velocity of S2-waves is more sensitive to
the fracture angle and decreases as fracture angle increases. Especially when the fracture strike coincides with the propagation plane and is parallel to the propagation direction, the fracture will cause intense variation in the S-waves velocity. Conversely, the P-waves velocity of all the samples has little difference in the direction of \( \sigma_h \), which demonstrates that the P-waves velocity is only related to the external stresses applied and independent of the fracture angle and strike.

Figure 5. Group A: the S-waves velocity (S1/S2) and P-waves velocity measured along three orthogonal axes with loading and unloading steps (\( \sigma_H \) direction: shear wave S1 propagates in the \( \sigma_H - \sigma_h \) plane, and shear wave S2 propagates in the \( \sigma_H - \sigma_v \) plane; \( \sigma_h \) direction: shear wave S1 propagates in the \( \sigma_h - \sigma_H \) plane, and shear wave S2 propagates in the \( \sigma_h - \sigma_v \) plane)

Figure 6. Group B: the S-waves velocity shear wave velocity (S1/S2) and P-waves velocity measured along three orthogonal axes with loading and unloading steps (\( \sigma_H \) direction: shear wave S1 propagates in the \( \sigma_H - \sigma_h \) plane, and shear wave S2 propagates in the \( \sigma_H - \sigma_v \) plane; \( \sigma_h \) direction: shear wave S1 propagates in the \( \sigma_h - \sigma_H \) plane, and shear wave S2 propagates in the \( \sigma_h - \sigma_v \) plane)
Conclusion

A novel true-triaxial geophysical test apparatus and analysis method are presented in this work, which tests stress-strain behavior, acoustic wave velocity, and anisotropic permeability of fractured deep tight sandstone simultaneously under true-triaxial stress in a laboratory environment. The stress-strain curves show that the sample is always in elastic deformation. The fractures can promote the deformation of the sample, but there is no apparent relationship between strain and fracture angle. The velocities of P-waves and S-waves increase linearly and show obvious anisotropy with the stress loading. The shear wave velocity (S1 and S2) is much more sensitive to fracture occurrence and angles. The permeabilities decrease exponentially and display anisotropy in the three principal stress directions with stress loading. The stress sensitivity of the permeability of the fractured samples is stronger than that of intact samples, especially with fracture strike parallel to $\sigma_h$. The experimental results reveal the stress sensitivity and anisotropy of rock mechanical and petrophysical properties under in situ stress conditions, provide an innovative method to accurately measure anisotropic rock properties, offer a new idea about fracture identification, and have profound significance for exploration and development of tight reservoirs.

Reference

[1] Dereuil A A, Birgenheier L P, McLennan J. Effects of Anisotropy and Saturation on Geomechanical Behavior of Mudstone[J]. Journal of Geophysical Research: Solid Earth, 2019, 124(8).
[2] Schubnel A, Benson P M, BD Thompson, et al. Quantifying Damage, Saturation and Anisotropy in Cracked Rocks by Inverting Elastic Wave Velocities[J]. Birkhäuser Basel.
[3] Bonnelle A, Schubnel A, David C, et al. Strength anisotropy of shales deformed under uppermost crustal conditions[J]. Journal of Geophysical Research Solid Earth, 2017, 122(1):110-129.
[4] Cook N G W. The failure of rock[J]. International Journal of Rock Mechanics & Mining Sciences & Geomechanics Abstracts, 1965, 2:389–403.
[5] Hudson J A, Crouch S L, Fairhurst C. Soft, stiff and servo-controlled testing machines: a review with reference to rock failure[J]. Engineering Geology, 1972, 6(3):155-189.
[6] Zong Y, Han L, Wei J, et al. Mechanical and damage evolution properties of sandstone under triaxial compression[J]. International Journal of Mining Science and Technology, 2016, 26(004):601-607.
[7] Xu G, Niu S, Jing H, et al. Experimental study of energy features of sandstone under loading and unloading[J]. Rock and Soil Mechanics, 2011, 32(12): 3611-3617.
[8] Mavko G, Mukerji T, Godfrey N. Predicting stress-induced velocity anisotropy in rocks[J]. Geophysics, 1995, 60(4):1081-1087.
[9] Wu B, King M S, Hudson J A. Stress-induced ultrasonic wave velocity anisotropy in a sandstone[J]. International Journal of Rock Mechanics & Mining Sciences & Geomechanics Abstracts, 1991, 28(1):101-107.
[10] Vernik L, Nur A (1992) Ultrasonic velocity and anisotropy of hydrocarbon source rocks. Geophysics 57:727–735
[11] Helmut Dührast, P. N. J. Rasolofosaon, Siegfried Siegesmund. P-wave velocity and permeability distribution of sandstones from a fractured tight gas reservoir. Geophysics 2002, 67 (1): 241–253.
[12] Zhang G, Li H, Wang M, et al. Crack-induced acoustic emission and anisotropy variation of brittle rocks containing natural fractures[J]. Journal of Geophysical and Engineering, 2019, 16(3).
[13] Zeng K, Xu J X, He P, et al. Experimental Study on Permeability of Coal Sample Subjected to Triaxial Stresses[J]. Procedia Engineering, 2011, 26(1):1051-1057.
[14] Heller R, Vermyleen J, Zoback M. Experimental investigation of matrix permeability of gas shales[J]. AAPG Bull, 2014, 98(5): 975-995.
[15] Li Y, Dong P, He Z, et al. Stress sensitivity analysis of permeability and threshold pressure gradient in low-permeability reservoir[J]. Petroleum Geology and Recovery Efficiency, 2016.
[16] Shi L, Zeng Z, Bai B, et al. Effect of the intermediate principal stress on the evolution of mudstone permeability under true triaxial compression[J]. Greenhouse Gases Science & Technology, 2017.
[17] Li X, Wu Z, Takahashi M, et al. Permeability Anisotropy of Shirahama Sandstone under True Triaxial Stresses.[J]. Proceedings of the Japan Society of Civil Engineers, 2010(708):1-11.
[18] Liu Y, Yin G, Zhang D, et al. Directional permeability evolution in intact and fractured coal subjected to true-triaxial stresses under dry and water-saturated conditions[J]. International Journal of Rock Mechanics and Mining Sciences, 2019, 119.
[19] Shi C, Wang Z, Zhu W, et al. Fracture characteristic and its impact on reservoir quality of ultra-deep reservoir in Dabei region, Kelasu tectonic belt, Kuqa Depression, Tarim Basin[J]. Natural Gas Geoscience, 2020, 31(12): 1687-1699.
[20] Liu C, Zhang R, Zhang H, et al. Genesis types and geological significance of micropore in tight sandstone reservoirs: a case study of ultra-deep reservoirs in Kuqa foreland thrust belt[J]. Acta petrolei Sinica, 2017,38(2):150-159.
[21] Morshed S M, Chesnokov E M, Vikhoreva A A. Biot effective stress parameter in poroelastic anisotropic media, static and dynamic case[J]. Geophysical Prospecting, 2020.