

Original article

Lode angle dependence of permeability along the three principal directions in purple sandstone

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Abstract:

Previous studies have primarily examined the dependence of permeability in a single direction on true-triaxial principal stresses. However, reservoir rocks exhibit pronounced permeability anisotropy, and their principal stresses undergo dynamic alternation. Thus, clarifying how the Lode angle affects three-directional permeability is essential for hydrocarbon recovery. This study examines the permeability of purple sandstone along the three principal directions using a self-developed edge-sealed geophysical imaging cell. Tests are conducted under constant hydrostatic pressure with varying deviatoric stress and Lode angle. The findings reveal that all three-directional permeabilities vary non-monotonically with the Lode angle. Their relationships with deviatoric stress can be positive or negative depending on this angle, reversing between the two opposite loading and unloading conditions of the principal stresses. Permeability anisotropy, quantified by the ratio of the three-directional permeabilities, persists even under hydrostatic pressure due to internal heterogeneity. The anisotropy ratio also varies non-monotonically with the Lode angle but exhibits an approximately monotonic relationship with deviatoric stress at a constant Lode angle. A model is developed to characterize the dependence of permeability on the Lode angle, and its coefficients characterize directional differences in permeability sensitivity to effective principal stresses. A stronger Lode angle dependence corresponds to greater differences in stress sensitivity among the directions.

1. Introduction

In-situ stress in deep underground reservoirs is inherently three-dimensional, known as a true-triaxial state (Li et al., 2022; Xie et al., 2024; Zhou et al., 2025). Under the coupled influence of inherent directional differences and true-triaxial stress loading (Guo et al., 2024; Li et al., 2025), the permeability of reservoir rocks is not uniform but exhibits significant anisotropy (Nasser et al., 2014; Yu et al., 2026). This directional dependence of permeability directly governs the migration pathways and flow capacity of fluids within the porous medium, thereby influencing reservoir productivity and

recovery potential (Chen et al., 2016b; Jiang et al., 2021). However, due to engineering disturbances, such as fluid injection-production operations and hydraulic fracturing (Hong et al., 2023; Zou et al., 2026), reservoir rocks commonly experience stress fluctuations around an initial stress state (Zhang et al., 2025). During this process, the relative relationships among the three principal stresses change continuously, inducing repeated closure and reopening of the internal fractures and flow pathways, thereby altering permeability characteristics, as shown in Fig. 1. At a given stress level, the relative distribution of the three principal stresses can be quantitatively characterized by the Lode angle (Liu et al., 2024). Thus, quan-

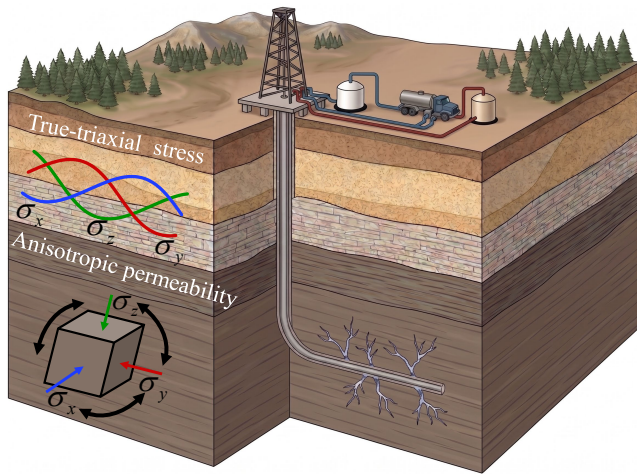


Fig. 1. Schematic diagram of reservoir exploitation.

titative analyses of the Lode angle dependence of three-directional permeability evolution is vital for enhancing oil and gas production efficiency, optimizing reservoir management and formulating effective enhanced recovery strategies.

Over the past decades, various tests have been conducted to investigate the permeability characteristics of rocks. For instance, variations in the axial permeability of cylindrical rock samples under varying confining/hydrostatic pressure conditions have been investigated extensively (Dong et al., 2010; Zhang et al., 2015; Wang et al., 2017), with permeability generally decreasing exponentially as confining/hydrostatic pressure increases (Liu et al., 2020a; Wang and Cheng, 2020). In addition, the axial permeability characteristics of cylindrical rock samples under triaxial compression state have been widely studied (Alkan, 2009; Yang et al., 2015; Carbillot et al., 2025). Deviatoric stress-induced damage leads to substantial non-monotonic changes in permeability (Chen et al., 2016a; Liu et al., 2020b; Liu et al., 2025).

The aforementioned studies focus on the axial permeability characteristics of cylindrical rock samples under one-dimensional or two-dimensional stress conditions. However, reservoir rocks are typically subjected to three-dimensional stress states (Jiang et al., 2021). Consequently, findings from these studies cannot fully satisfy the practical requirements of reservoir development. With advances in experimental instrumentation, researchers have increasingly analyzed the permeability characteristics of rocks under true-triaxial stress conditions, including sandstone (Li et al., 2002; Lu et al., 2019), shale (Li et al., 2016; Liu et al., 2019a; Wang et al., 2023), coal (Liu et al., 2018, 2019b, 2019c), and mudstone (Gong et al., 2025). The permeability of cubic rock samples exhibits anisotropic stress sensitivity with respect to the principal stresses acting along the three axes, resulting in more pronounced nonlinearity and non-monotonicity variations in rock permeability under true-triaxial stress conditions.

Nevertheless, current permeability tests under true-triaxial stress conditions have two notable limitations: (1) the inability to measure and analyze multi-directional permeability, and (2) the lack of consideration for the Lode angle dependence of permeability. Existing studies have shown that rock permeability exhibits pronounced directional dependence (Pan et

al., 2015; Yan et al., 2019; Liu et al., 2020c). However, with few exceptions (Nasseri et al., 2014; Sato et al., 2018; Jiang et al., 2021), most true-triaxial testing apparatuses are limited to measuring permeability in a single direction, and corresponding studies are likewise confined to the characteristics of unidirectional permeability. Moreover, most existing true-triaxial permeability tests primarily focus on the dependence of permeability on principal stresses, while they overlook the characteristic of its dependence on the Lode angle. The Lode angle characterizes the relative magnitudes of the three principal stresses, and the resulting permeability response reflects its sensitivity to the directional differences among these stresses at a given stress level. Only a handful of studies have examined the dependence of unidirectional permeability on the Lode angle (Baizhanov et al., 2019; Lu et al., 2019; Liu et al., 2021), leaving the underlying mechanisms largely unclear. To better understand the evolution mechanisms of rock permeability, a quantitative analysis of three-directional permeability with respect to the Lode angle is necessary.

In this study, a self-developed geophysical imaging cell is utilized to measure the permeability of purple sandstone in three principal directions under true-triaxial stress conditions. To investigate its Lode-angle dependence, true-triaxial loading-unloading paths with varying Lode angles and deviatoric stresses under constant hydrostatic pressure are adopted. Furthermore, the evolution of permeability in three principal directions and its anisotropy ratios with Lode angle and deviatoric stress are quantitatively analyzed. Subsequently, the stress sensitivity differences among the three-directional permeabilities are quantitatively evaluated based on the proposed permeability model. Finally, the quantitative dependence of three-directional permeability and its ratio on deviatoric stress and Lode angle is presented using the proposed model.

2. Experimental scheme

2.1 Sample preparation

Purple sandstone (15% porosity) was selected for permeability tests. The intact sandstone block was cut into cubic specimens with dimensions of $100 \times 100 \times 100 \text{ mm}^3$. The specimens were carefully polished, ensuring that surface unevenness and non-perpendicularity were kept below 0.02 mm. Subsequently, chamfers of 3 mm depth were applied to all twelve edges to facilitate edge sealing, as shown in Fig. 2. Based on the optical thin-section observations, the sandstone was mainly composed of quartz and feldspar. The particle size ($\Phi = -\log_2 r$) was predominantly in the fine-sand range ($[2 < \Phi \leq 3] = 72\%$), with the remaining particles mainly distributed in the very-fine-sand ($[3 < \Phi \leq 4] = 13\%$) and medium-sand ($[1 < \Phi \leq 2] = 15\%$) ranges. Mercury intrusion porosimeter results indicated that the porosity of the purple sandstone was primarily contributed by macropores ranging from 10^4 to 10^5 nm (40%), mesopores ranging from 10^3 to 10^4 nm (15%), and transition pores ranging from 10^1 to 10^3 nm (35%) (Hu et al., 2024).

Previous studies have shown that, although the three-directional permeability levels are generally comparable among different rock specimens, the relationships among the

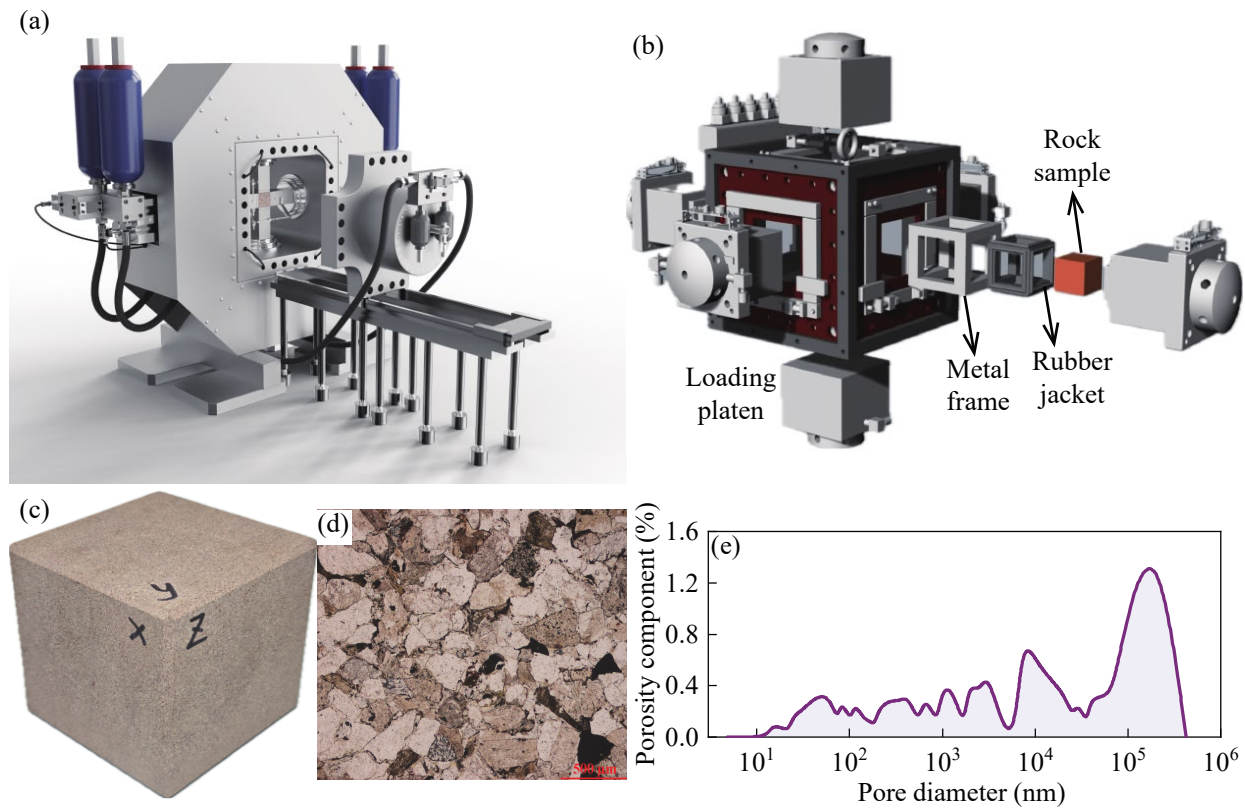


Fig. 2. The three-directional permeability testing system consists of (a) a true-triaxial loading frame, (b) a geophysical imaging cell, (c) cubic rock sample with its (d) optical thin section and (e) pore-size distribution.

three-directional permeabilities can vary to different degrees (Nasseri et al., 2014). To avoid the influence of specimen-to-specimen variability on the three-directional permeability, this study focuses on the permeability results obtained from a single sandstone specimen. Future studies are also planned to investigate various types of rock specimens to further assess the generality of Lode angle dependence. Prior to the formal tests, the specimens were subjected to repeated hydrostatic loading and unloading to reduce the influence of stress loading-unloading sequence on the permeability results. Specifically, three loading-unloading cycles of hydrostatic pressure were conducted, with unloading initiated once $I_1 = 90$ MPa was reached in each loading cycle. During the above loading-unloading tests, the rock specimen was not subjected to deviatoric stress and was therefore assumed not to undergo damage. After repeated loading-unloading cycles, the loading and unloading stress sensitivities of the rock specimen gradually converge and reach a stable state (Wang et al., 2017). This behavior allows the permeability to be assumed to depend only on the stress state, without considering the effect of loading-unloading history (sequence). A similar assumption has also been adopted in previous permeability studies (Lu et al., 2019). However, this remains a limitation of the present study, and the effects of loading-unloading history on the three-directional permeability of rocks will be further investigated in future experiments.

2.2 Experimental equipment

Permeability measurements in the three principal directions were conducted using a geophysical imaging cell with true-triaxial loading frame, both of which were independently developed by Tianjin University, as presented in Fig. 2. The cubic specimen was sequentially encased in a rubber jacket and a metal frame before being positioned at the center of the geophysical imaging chamber, as presented in Fig. 2. A rubber membrane within the loading platens applied sealing pressure to the cubic specimen, ensuring effective edge sealing in the geophysical imaging cell. In addition, the geophysical imaging cell incorporated fluid channels and pressure sensors to apply and monitor pore pressure at each surface of the cubic specimen. Subsequently, the geophysical imaging cell was positioned within the true-triaxial loading frame for permeability testing.

2.3 Experimental procedure

A constant hydrostatic pressure was maintained throughout the test to examine the Lode angle dependence of permeability along the three principal directions. Initially, the principal stresses in the three directions were applied up to 30 MPa to measure the permeability under hydrostatic pressure conditions (isotropic stress state). Subsequently, permeability measurements were performed under varying deviatoric stresses and Lode angles while keeping the hydrostatic pressure con-

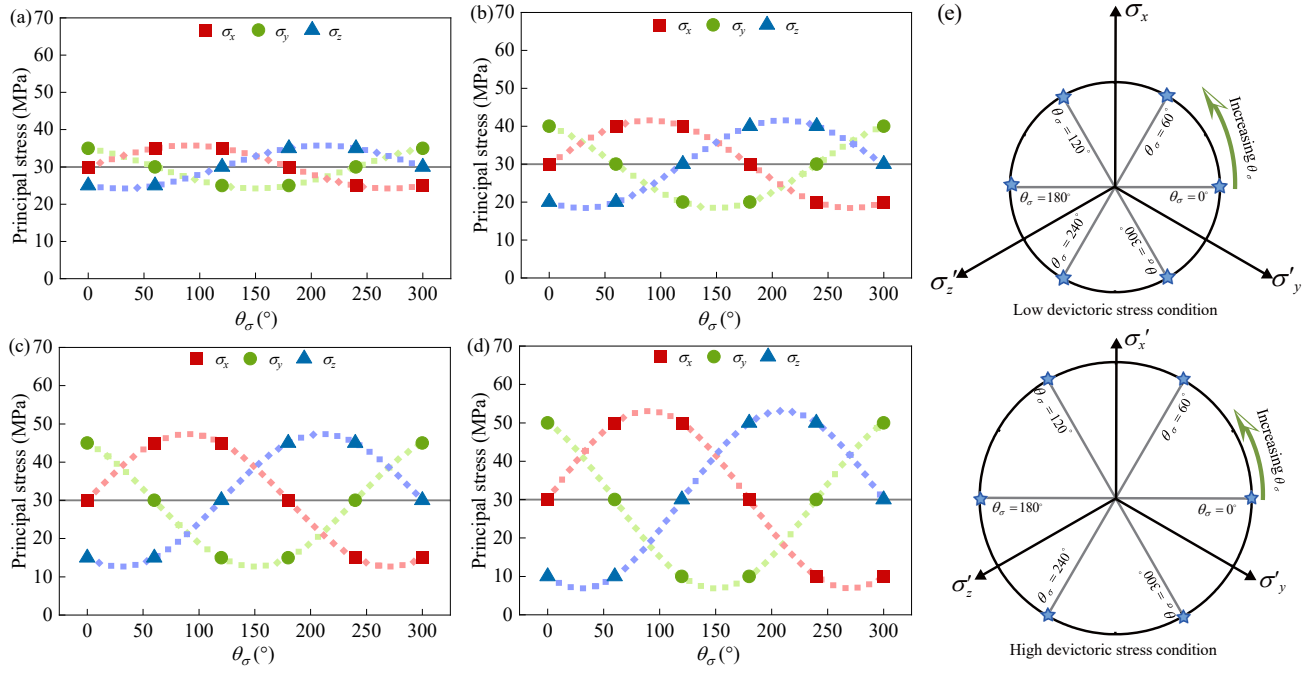


Fig. 3. Principal stress loading-unloading path under (a) $\sqrt{J_2} = 5$ MPa, (b) $\sqrt{J_2} = 10$ MPa, (c) $\sqrt{J_2} = 15$ MPa and (d) $\sqrt{J_2} = 20$ MPa, and (e) schematic of stress distribution in the deviatoric plane.

stant, as shown in Fig. 3. The relationships among principal stresses, hydrostatic pressure, deviatoric stress, and Lode angle are expressed as follows (Lu et al., 2019):

$$\sigma_x = \frac{2\sqrt{J_2}}{\sqrt{3}} \sin \theta_\sigma + \frac{I_1}{3} \quad (1)$$

$$\sigma_y = \frac{2\sqrt{J_2}}{\sqrt{3}} \sin \left(\theta_\sigma + \frac{2}{3}\pi \right) + \frac{I_1}{3} \quad (2)$$

$$\sigma_z = \frac{2\sqrt{J_2}}{\sqrt{3}} \sin \left(\theta_\sigma - \frac{2}{3}\pi \right) + \frac{I_1}{3} \quad (3)$$

where σ_x , σ_y and σ_z represent the principal stresses along the three directions, respectively; $\sqrt{J_2}$ represents the deviatoric stress; I_1 represents the first invariant of stress tensor, accounting for the level of hydrostatic pressure (Wang et al., 2024, 2026); θ_σ represents the Lode angle for stress (Wang et al., 2024, 2026). Specifically, θ_σ ranges from -30° to 30° under the condition of $\sigma_y > \sigma_x > \sigma_z$, from 30° to 90° under the condition of $\sigma_x > \sigma_y > \sigma_z$, from 90° to 150° under the condition of $\sigma_x > \sigma_z > \sigma_y$, from 150° to 210° under the condition of $\sigma_z > \sigma_x > \sigma_y$, from 210° to 270° under the condition of $\sigma_z > \sigma_y > \sigma_x$, and from 270° to 330° under the condition of $\sigma_y > \sigma_z > \sigma_x$. It is worth noting that the Lode angle in the conventional definition ranges from -30° to 30° . Therefore, the corresponding offset should be added for each angular interval, and its value is equal to the difference between the initial values of each interval and -30° .

In this study, four deviatoric stress levels (5 MPa, 10 MPa, 15 MPa, and 20 MPa) coupled with six Lode angle levels (0° , 60° , 120° , 180° , 240° , 300°) were selected to conduct permeability tests under constant hydrostatic pressure ($I_1 = 90$ MPa). The adopted deviatoric stress levels were relatively low, and the effect of damage on rock permeability was therefore

assumed to be negligible. Compared with the initial hydrostatic pressure state, one principal stress direction remained constant while the other two directions varied in opposite magnitudes, as shown in Fig. 3. The variation in principal stress ($\Delta\sigma$) was proportional to the deviatoric stress. Specifically, $\Delta\sigma = \pm 5$ MPa under the condition of $\sqrt{J_2} = 5$ MPa, $\Delta\sigma = \pm 10$ MPa under the condition of $\sqrt{J_2} = 10$ MPa, $\Delta\sigma = \pm 15$ MPa under the condition of $\sqrt{J_2} = 15$ MPa, and $\Delta\sigma = \pm 20$ MPa under the condition of $\sqrt{J_2} = 20$ MPa. Besides, the principal stress variations under $\theta_\sigma + 180^\circ$ condition, as shown in Fig. 3.

The experiments were conducted at room temperature (20°C). A gas mass flow meter with a minimum flow rate accuracy of 1 mL/min was used to measure the gas flow rate. During the experiments, the Lode angle was increased from 0° to 300° , after which the next higher deviatoric stress level was applied. Once the preset stress state was reached, the permeability was determined under a constant upstream pressure (absolute value 0.5 MPa) using a steady-state approach. The downstream surface was directly exposed to the atmosphere. The permeabilities in the three directions were measured sequentially (x , y , z) by adjusting the corresponding valves. Once the flow rate reached a steady state, the apparent permeability could be calculated using Darcy's law (Shi et al., 2021; Gao et al., 2023), given by (Lu et al., 2019):

$$k = \frac{\mu Q}{A} \frac{2LP_o}{P_{up}^2 - P_{do}^2} \quad (4)$$

where μ represents the viscosity of helium at room temperature ($1.95\text{E-}5$ Pa·s), L denotes the specimen length, A denotes its cross-sectional area, Q denotes the flow rate, P_{up} denotes the inlet pressure, P_{do} denotes the outlet pressure, and P_o is

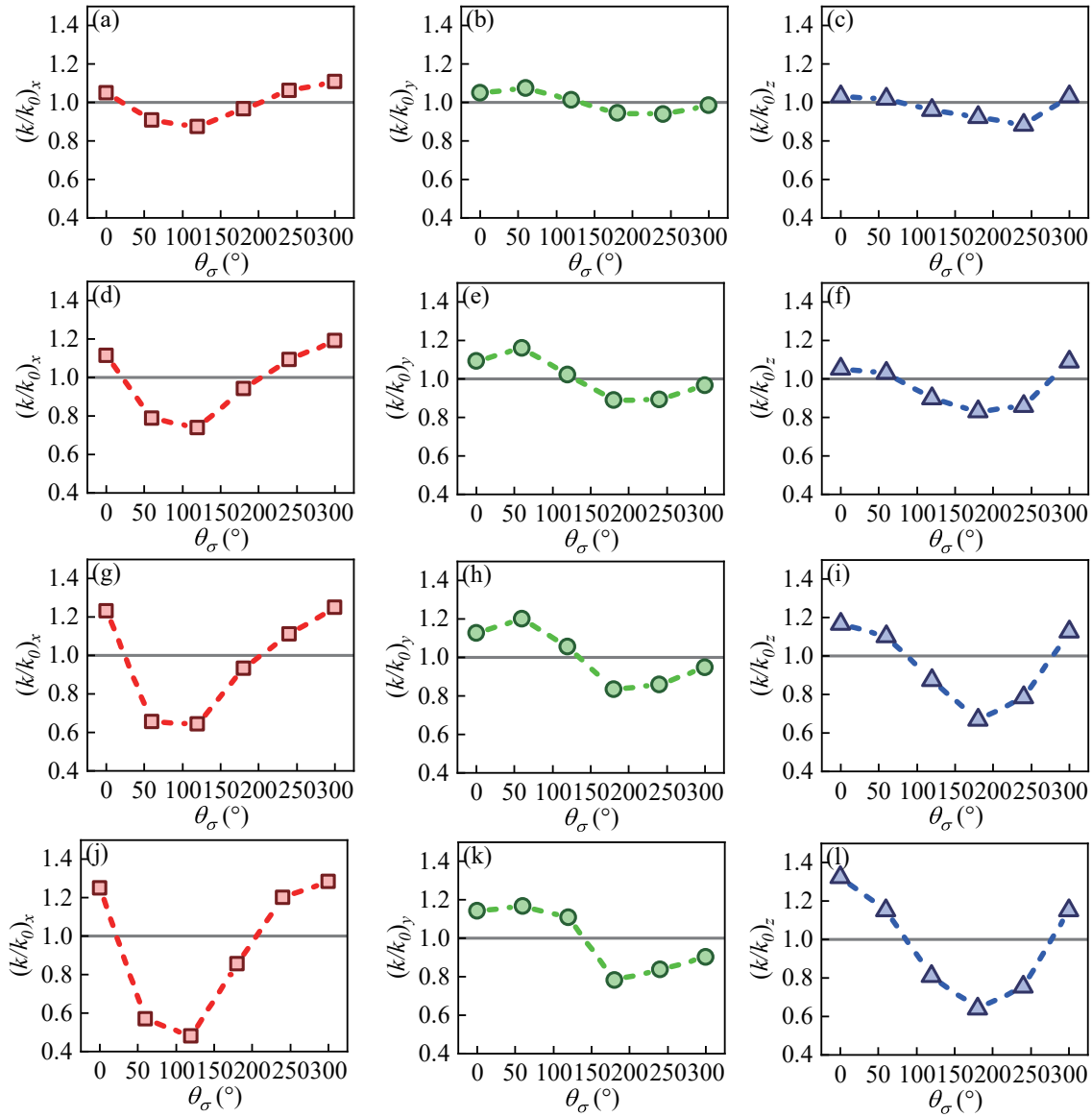


Fig. 4. Dependence of normalized three-directional permeability on Lode angle under (a)-(c) $\sqrt{J_2} = 5$ MPa, (d)-(f) $\sqrt{J_2} = 10$ MPa, (g)-(i) $\sqrt{J_2} = 15$ MPa and (j)-(l) $\sqrt{J_2} = 20$ MPa, where k_0 represents the initial permeability under hydrostatic pressure conditions.

the atmospheric pressure.

3. Experimental results

3.1 Evolution of three-directional permeability

The three-directional permeabilities were normalized by the initial permeabilities under hydrostatic pressure condition. The dependence of normalized three-directional permeability on Lode angle is shown in Fig. 4. It can be seen that with increasing Lode angle, $(k/k_0)_x$ and $(k/k_0)_z$ exhibit a decreasing-then-increasing trend, whereas $(k/k_0)_y$ shows an increasing-then-decreasing-then-increasing pattern. Similar non-monotonic variations have also been reported in a previous study (Lu et al., 2019). For the current deviatoric stress state, the permeability k_x ranges from approximately 50% to 130%

of the initial value, k_y from about 80% to 120%, and k_z from roughly 65% to 130%, indicating that the dependence of permeability on Lode angle is significant and cannot be overlooked.

The dependence of three-directional permeability on Lode angle is shown in Fig. 5. The initial three-directional permeability under hydrostatic pressure exhibits anisotropy due to internal heterogeneity, a phenomenon similarly reported in the literature (Nasseri et al., 2014; Sato et al., 2018; Jiang et al., 2021). Specifically, the initial permeability exhibits the following relationship: $(k_x)_0 > (k_z)_0 > (k_y)_0$. As the Lode angle and deviatoric stress conditions vary, the three-directional permeabilities exhibit non-monotonic variations, which in turn alters the relative magnitudes among them. The above phenomenon is also referred to as stress-induced

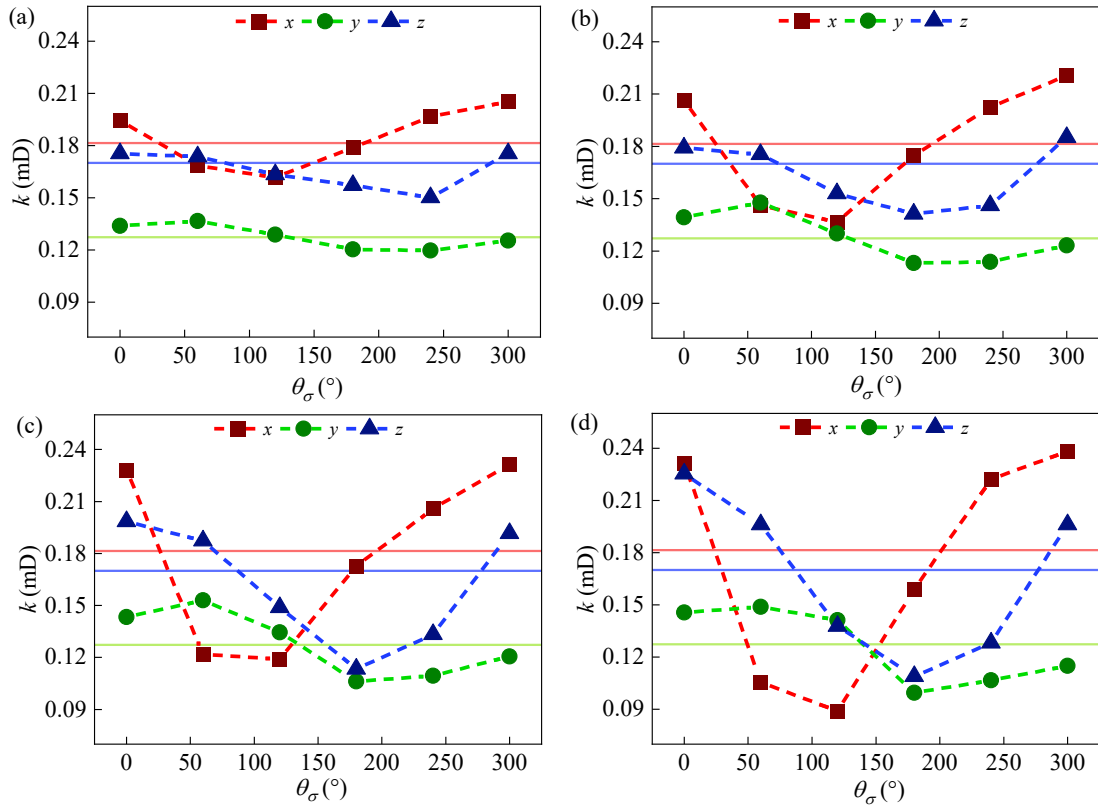


Fig. 5. Dependence of three-directional permeability on Lode angle under (a) $\sqrt{J_2} = 5$ MPa, (b) $\sqrt{J_2} = 10$ MPa, (c) $\sqrt{J_2} = 15$ MPa and (d) $\sqrt{J_2} = 20$ MPa. The solid lines represent initial permeability under hydrostatic pressure conditions.

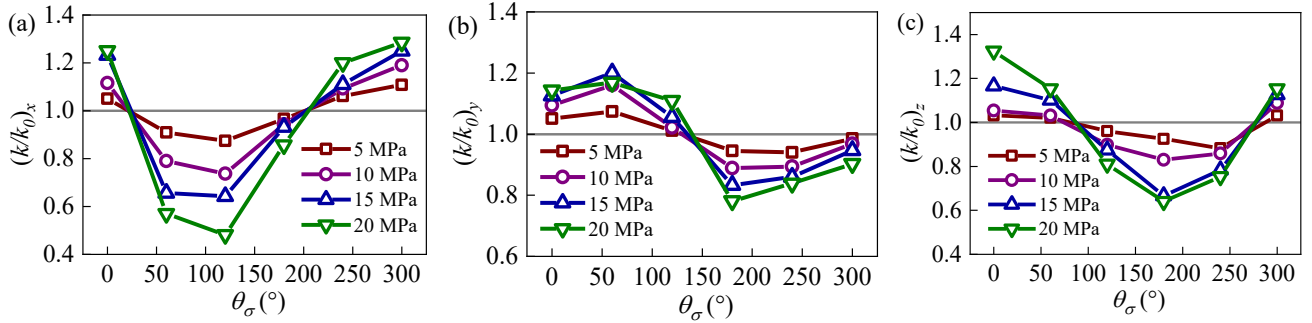


Fig. 6. Dependence of normalized three-directional permeability on deviatoric stress, including (a) x -directional permeability, (b) y -directional permeability, and (c) z -directional permeability.

anisotropy, which essentially arises from differences in the stress sensitivity of permeability along the three principal directions. The dependence of normalized permeability on deviatoric stress is presented in Fig. 6. Except for a few cases, the magnitude of permeability variation is positively correlated with the deviatoric stress. Under the condition of $\theta_\sigma = 60^\circ$, the variation magnitude of $(k/k_0)_y$ initially increases and then slightly decreases with increasing deviatoric stress. Moreover, it is worth noting that the three-directional permeability variations under the θ_σ condition are opposite to those under the $\theta_\sigma + 180^\circ$ condition. This phenomenon is related to the differences in principal stress loading/unloading and the sensitivity of permeability to principal stresses in different directions, which will be analyzed in detail in the

following sections.

3.2 Three-directional permeability anisotropy

In this study, permeability ratios are introduced to quantitatively characterize directional anisotropy (k_y/k_x , k_z/k_x and k_z/k_y). Higher values of $|k_i/k_j - 1|$ correspond to stronger anisotropy. The variation in the anisotropy ratios with Lode angle is shown in Fig. 7. With increasing Lode angle, k_y/k_x exhibits an increasing-then-decreasing trend, k_z/k_x exhibits an increasing-then-decreasing-then-increasing trend, whereas k_z/k_y shows a decreasing-then-increasing pattern. For the current deviatoric stress state, the anisotropy ratio k_y/k_x ranges from approximately 0.5 to 1.5, k_z/k_x from about 0.6 to 1.8, and

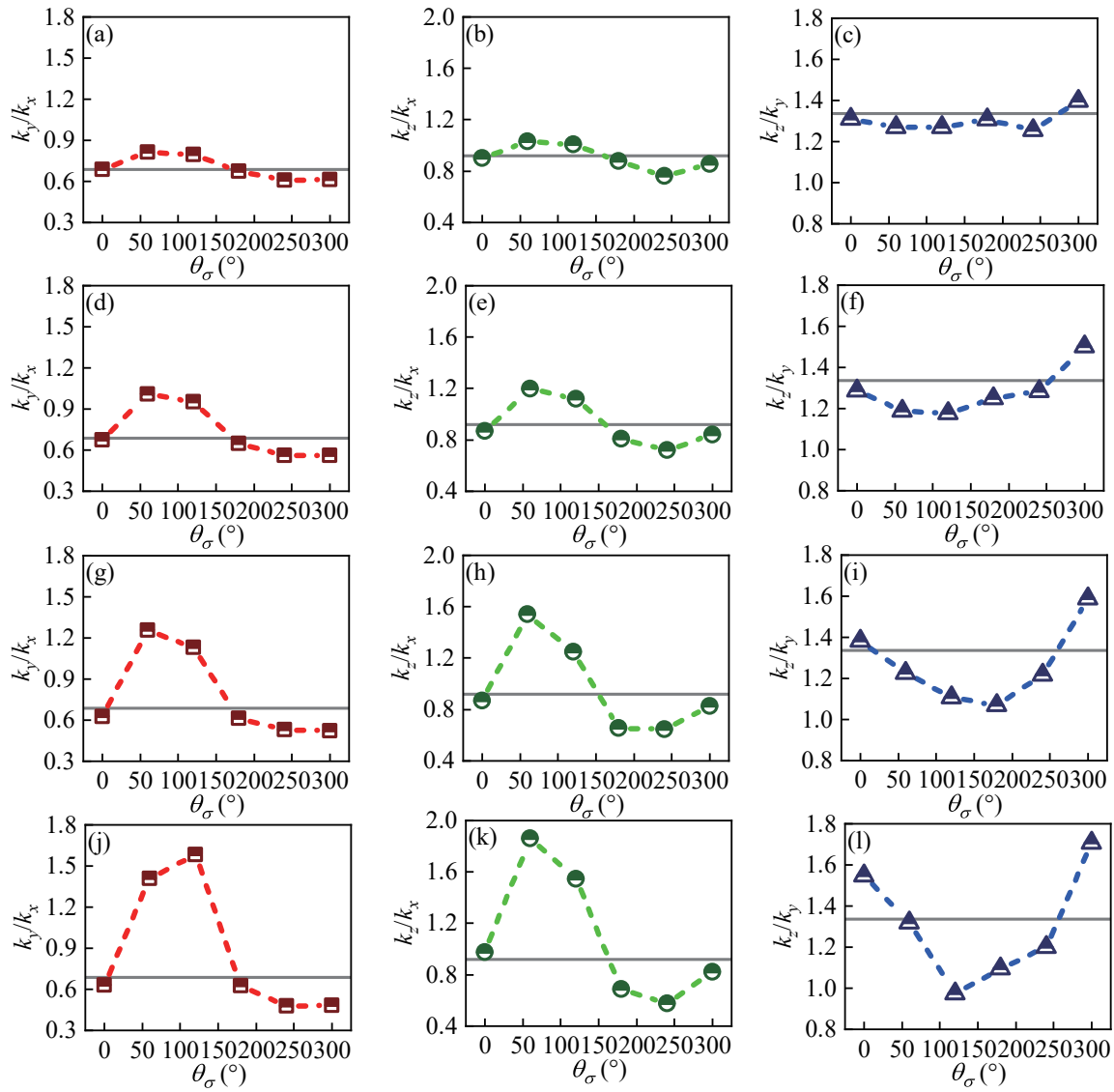


Fig. 7. Dependence of anisotropy ratio on Lode angle under (a)-(c) $\sqrt{J_2} = 5$ MPa, (d)-(f) $\sqrt{J_2} = 10$ MPa, (g)-(i) $\sqrt{J_2} = 15$ MPa and (j)-(l) $\sqrt{J_2} = 20$ MPa. The solid lines represent the initial anisotropy ratio under hydrostatic pressure conditions.

k_z/k_y from roughly 1 to 1.7, indicating that the dependence of permeability anisotropy on Lode angle is substantial and should not be overlooked. The comparison of anisotropy ratios is shown in Fig. 8. The differences in the initial anisotropy ratios under hydrostatic pressure conditions reflect the intrinsic anisotropy of the three-directional permeabilities. With variations in the Lode angle and deviatoric stress conditions, the relative magnitudes among the anisotropy ratios alternate, and this phenomenon becomes more pronounced with increasing deviatoric stress.

The dependence of anisotropy ratios on deviatoric stress is shown in Fig. 9. Similar to the variation in three-directional permeability, the variation amplitude of the anisotropy ratios is also proportional to the magnitude of the deviatoric stress. Except for a few cases, the variation of anisotropy ratio under the θ_σ condition is opposite to that under the $\theta_\sigma + 180^\circ$ condition. In both the $\theta_\sigma = 0^\circ$ and $\theta_\sigma = 180^\circ$ cases, k_y/k_x decreases with increasing deviatoric stress, although the change

is not significant. These variations are governed by the three-directional permeabilities, which in turn are controlled by their stress sensitivities.

4. Discussion

4.1 Influence of principal stress loading/unloading

The loading and unloading directions of the principal stresses are opposite under the θ_σ and $\theta_\sigma + 180^\circ$ conditions. The effect of principal stress loading/unloading on normalized permeability is shown in Fig. 10. The deviatoric stress ($\sqrt{J_2}$) is equal to $(\Delta\sigma_x - \Delta\sigma_y)/2$ under the above Lode angle conditions. Overall, the following trends are observed for the directional correlations of permeability with principal stress differences: $(k/k_0)_x$ shows a negative correlation with $\Delta\sigma_x - \Delta\sigma_y$ and $\Delta\sigma_x - \Delta\sigma_z$, while exhibits a positive correlation with $\Delta\sigma_y - \Delta\sigma_z$; $(k/k_0)_y$ shows a positive correlation with

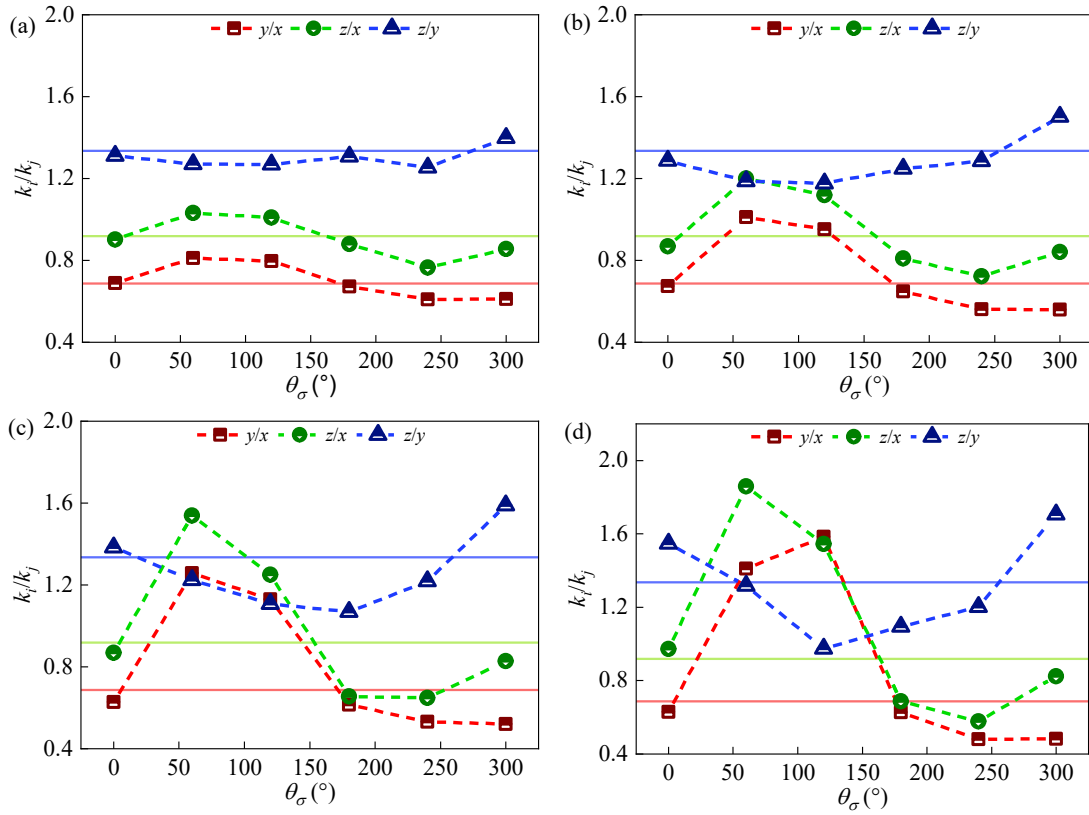


Fig. 8. Comparison of anisotropy ratios under (a) $\sqrt{J_2} = 5$ MPa, (b) $\sqrt{J_2} = 10$ MPa, (c) $\sqrt{J_2} = 15$ MPa and (d) $\sqrt{J_2} = 20$ MPa. The solid lines represent the initial anisotropy ratio under hydrostatic pressure conditions.

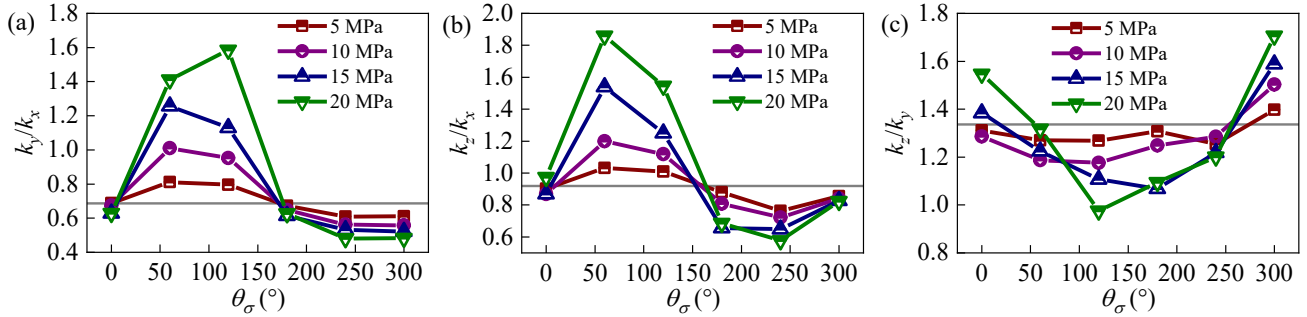


Fig. 9. Dependence of anisotropy ratio on deviatoric stress, including: (a) k_y/k_x , (b) k_z/k_x and (c) k_z/k_y . The solid lines represent the initial anisotropy ratio under hydrostatic pressure conditions.

$\Delta\sigma_x - \Delta\sigma_y$, $\Delta\sigma_x - \Delta\sigma_z$ and $\Delta\sigma_y - \Delta\sigma_z$. Conversely, $(k/k_0)_z$ shows a negative correlation with $\Delta\sigma_x - \Delta\sigma_y$, while it exhibits a positive correlation with $\Delta\sigma_x - \Delta\sigma_z$ and $\Delta\sigma_y - \Delta\sigma_z$.

The unloading of principal stresses causes permeability to recover, while that of principal stresses results in its decrease (Fan and Liu, 2019; Huang et al., 2021; Han et al., 2025). Therefore, these variations are primarily controlled by the differences in permeability sensitivity to the loading/unloading principal stresses. Permeability rebounds when it is more sensitive to the unloading principal stress, and it decreases when it is more sensitive to the loading principal stress. Specifically, the variations in permeability under the $\theta_\sigma = 300^\circ$ and $\theta_\sigma = 120^\circ$ conditions indicate that k_x and k_z are more sensitive to σ_x than σ_y , whereas k_y is more sensitive to σ_y ,

than σ_x . The variations in permeability under the $\theta_\sigma = 240^\circ$ and $\theta_\sigma = 60^\circ$ conditions indicate that k_y and k_z are more sensitive to σ_z than σ_x , whereas k_x is more sensitive to σ_x than σ_z . The variations in permeability under the $\theta_\sigma = 180^\circ$ and $\theta_\sigma = 0^\circ$ conditions indicate that k_x , k_y and k_z all exhibit higher sensitivity to σ_z than σ_y .

Under the combined effects of intrinsic anisotropy and differences in stress sensitivity, the relative magnitudes of the three-directional permeabilities change with variations in the Lode angle and loading/unloading principal stress, as shown in Fig. 11. In addition, comparisons of normalized permeability under varying Lode angle conditions are presented in Fig. 12. It can be seen that the dependence of permeability in the three principal directions on deviatoric stress varies under

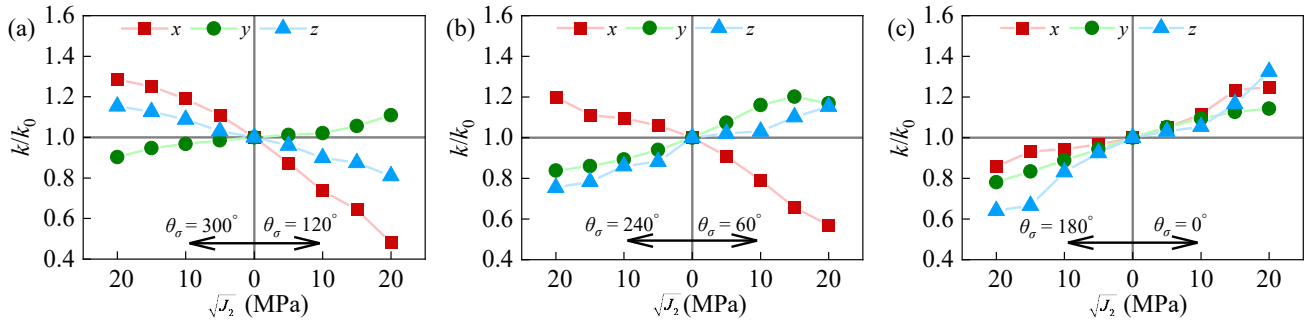


Fig. 10. Normalized permeability response to principal stress loading and unloading under (a) $\theta_\sigma = 300^\circ$ & $\theta_\sigma = 120^\circ$, (b) $\theta_\sigma = 240^\circ$ & $\theta_\sigma = 60^\circ$ and (c) $\theta_\sigma = 180^\circ$ & $\theta_\sigma = 0^\circ$.

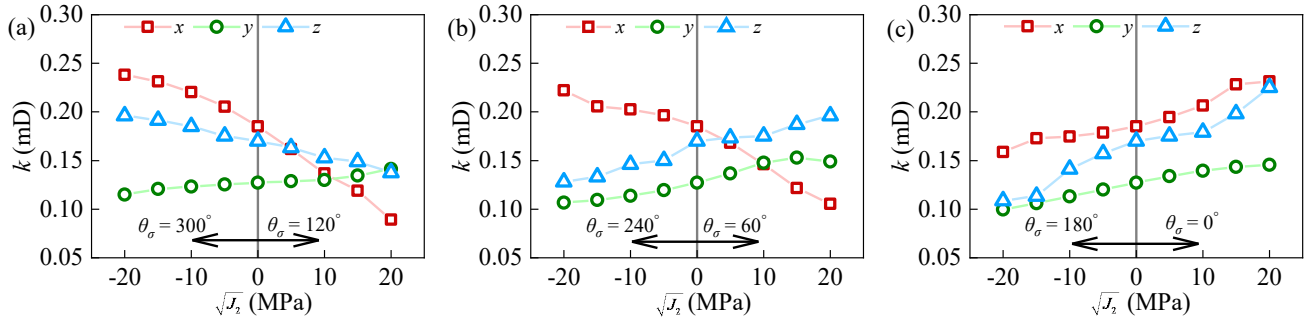


Fig. 11. Permeability response to principal stress loading and unloading under (a) $\theta_\sigma = 300^\circ$ & $\theta_\sigma = 120^\circ$, (b) $\theta_\sigma = 240^\circ$ & $\theta_\sigma = 60^\circ$ and (c) $\theta_\sigma = 180^\circ$ & $\theta_\sigma = 0^\circ$.

different Lode angle conditions. Specifically, k_x rebounds most noticeably under the condition of $\theta_\sigma = 300^\circ$, while it decreases most significantly under the condition of $\theta_\sigma = 120^\circ$. Similarly, k_y and k_z exhibit their maximum rebound under the conditions of $\theta_\sigma = 60^\circ$ and $\theta_\sigma = 0^\circ$, respectively. Besides, k_y and k_z exhibit their maximum decrease under the conditions of $\theta_\sigma = 180^\circ$.

4.2 Differences in stress sensitivity

Previous studies (Chen et al., 2015; Li et al., 2016; Zhang et al., 2016) have shown that permeabilities under true-triaxial stress can be described by an exponential permeability model, expressed as:

$$k_x = k_{x0} \exp(-C_{xx}\Delta\sigma_x - C_{xy}\Delta\sigma_y - C_{xz}\Delta\sigma_z) \quad (5)$$

$$k_y = k_{y0} \exp(-C_{yx}\Delta\sigma_x - C_{yy}\Delta\sigma_y - C_{yz}\Delta\sigma_z) \quad (6)$$

$$k_z = k_{z0} \exp(-C_{zx}\Delta\sigma_x - C_{zy}\Delta\sigma_y - C_{zz}\Delta\sigma_z) \quad (7)$$

where k_0 denotes the initial three-directional permeability under hydrostatic pressure conditions, k denotes the three-directional permeability, $i=x, y, z$; $j=x, y, z$; $\Delta\sigma_j$ denotes principal stress increment in the j -direction; and C_{ij} denotes the stress-sensitivity coefficient of permeability in the i -direction with respect to the principal stress in the j -direction. Higher values of C correspond to greater permeability sensitivity to the principal stress (Zhang et al., 2015, 2016).

The following expression describes the stress dependence of stress-sensitivity coefficient, expressed as (Jiang et al., 2021):

$$C = \frac{C_0}{1 + \xi \Delta\sigma} \quad (8)$$

where C_0 represents initial stress sensitivity coefficient, and ξ is used to control the variation rate of stress sensitivity coefficient.

Based on the above analysis, a novel effective permeability model along the three principal directions is proposed to capture the Lode angle dependence of permeability, which is expressed as:

$$k_x = k_{x0} \exp(-C_{xx}^e \Delta\sigma_x^e - C_{xy}^e \Delta\sigma_y^e - C_{xz}^e \Delta\sigma_z^e) \quad (9)$$

$$k_y = k_{y0} \exp(-C_{yx}^e \Delta\sigma_x^e - C_{yy}^e \Delta\sigma_y^e - C_{yz}^e \Delta\sigma_z^e) \quad (10)$$

$$k_z = k_{z0} \exp(-C_{zx}^e \Delta\sigma_x^e - C_{zy}^e \Delta\sigma_y^e - C_{zz}^e \Delta\sigma_z^e) \quad (11)$$

with:

$$C_{xx}^e = C_{xx\infty}^e + \frac{C_{xx\Delta}^e}{1 + \xi_{xx}^e \Delta\sigma_x^e} \quad (12)$$

$$C_{xy}^e = C_{xy\infty}^e + \frac{C_{xy\Delta}^e}{1 + \xi_{xy}^e \Delta\sigma_y^e} \quad (13)$$

$$C_{xz}^e = C_{xz\infty}^e + \frac{C_{xz\Delta}^e}{1 + \xi_{xz}^e \Delta\sigma_z^e} \quad (14)$$

$$C_{yx}^e = C_{yx\infty}^e + \frac{C_{yx\Delta}^e}{1 + \xi_{yx}^e \Delta\sigma_x^e} \quad (15)$$

$$C_{yy}^e = C_{yy\infty}^e + \frac{C_{yy\Delta}^e}{1 + \xi_{yy}^e \Delta\sigma_y^e} \quad (16)$$

$$C_{yz}^e = C_{yz\infty}^e + \frac{C_{yz\Delta}^e}{1 + \xi_{yz}^e \Delta\sigma_z^e} \quad (17)$$

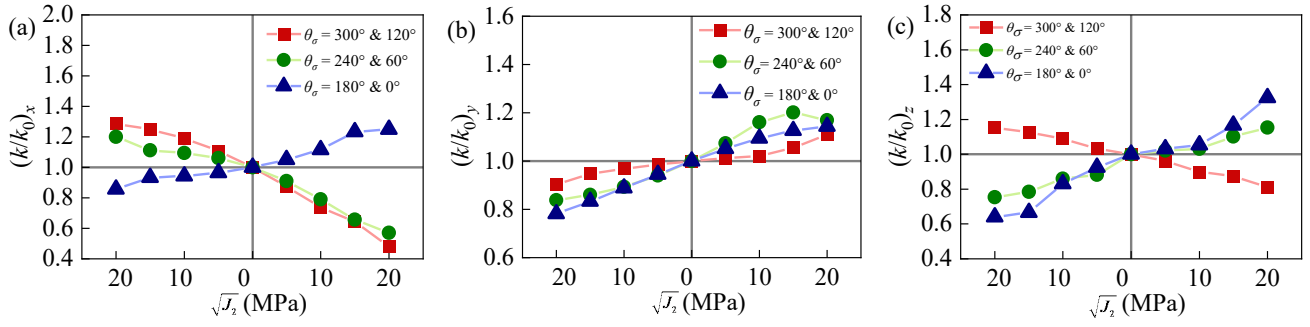


Fig. 12. Comparisons of normalized permeability under varying Lode angle conditions, including (a) x -directional permeability, (b) y -directional permeability, and (c) z -directional permeability.

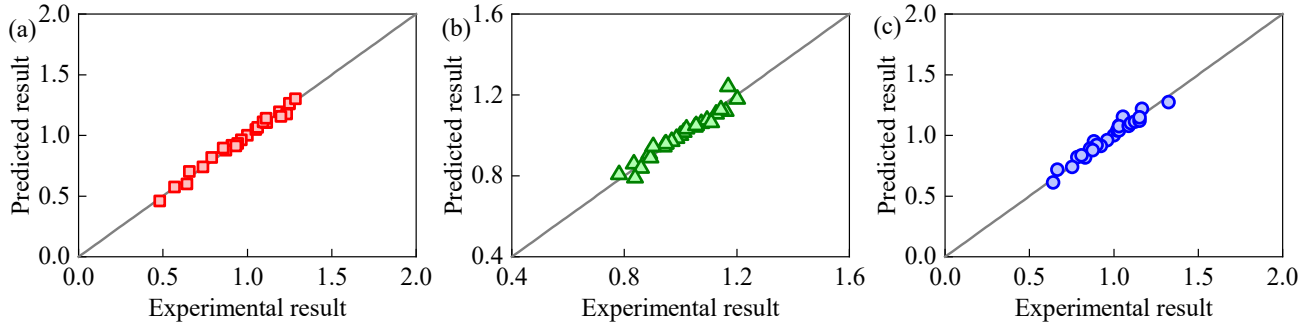


Fig. 13. Comparisons between predicted and experimental results, including (a) x -directional permeability, (b) y -directional permeability, and (c) z -directional permeability.

Table 1. Model parameters.

Parameter	Value	Parameter	Value	Parameter	Value
C_{xx}^e	1.04E-5	C_{yx}^e	2.31E-2	C_{zx}^e	3.69E-2
$C_{xx\Delta}^e$	5.6E-2	$C_{yx\Delta}^e$	3E-3	$C_{zx\Delta}^e$	8.51E-4
ξ_{xx}^e	-1.1E-2	ξ_{yx}^e	1.5E-2	ξ_{zx}^e	1.5E-2
C_{xy}^e	2.3E-2	C_{yy}^e	2.58E-2	C_{zy}^e	1.58E-5
$C_{xy\Delta}^e$	9.7E-3	$C_{yy\Delta}^e$	3.3E-3	$C_{zy\Delta}^e$	3E-2
ξ_{xy}^e	1.05E-3	ξ_{yy}^e	-1.24E-2	ξ_{zy}^e	-2.2E-3
C_{xz}^e	2.6E-6	C_{yz}^e	1.09E-5	C_{zz}^e	3.1E-2
$C_{xz\Delta}^e$	4.1E-2	$C_{yz\Delta}^e$	3.76E-2	$C_{zz\Delta}^e$	1.58E-2
ξ_{xz}^e	3.48E-3	ξ_{yz}^e	-2E-3	ξ_{zz}^e	-1.45E-2

$$C_{zx}^e = C_{zx}^e + \frac{C_{zx\Delta}^e}{1 + \xi_{zx}^e \Delta \sigma_x^e} \quad (18)$$

$$C_{zy}^e = C_{zy}^e + \frac{C_{zy\Delta}^e}{1 + \xi_{zy}^e \Delta \sigma_y^e} \quad (19)$$

$$C_{zz}^e = C_{zz}^e + \frac{C_{zz\Delta}^e}{1 + \xi_{zz}^e \Delta \sigma_z^e} \quad (20)$$

where C^e represents the effective coefficient of permeability with respect to effective principal stress increment ($\Delta \sigma^e = \Delta \sigma - \alpha \Delta p$) (Huang et al., 2024); α denotes effective stress coefficient, and p is pore pressure. In this study, p remains constant; therefore, $\Delta \sigma^e$ values are equal to $\Delta \sigma$. C_{∞}^e , C_{Δ}^e and ξ^e are used to control the variation in C^e with $\Delta \sigma^e$. The value

of C^e is positively correlated with both C_{∞}^e and C_{Δ}^e . When $\xi^e > 0$, C^e is negatively correlated with $\Delta \sigma^e$, whereas when $\xi^e < 0$, this correlation is positive. Besides, a larger value of ξ^e results in a greater variation rate in C^e . Positive values for $\Delta \sigma^e$ represent loading, while negative values indicate unloading.

The least-squares method was used to determine the model parameters, as shown in Table 1. The comparisons between predicted and experimental results are shown in Fig. 13. The root means square error (RMSE) was employed to evaluate the fitting accuracy, given by:

$$\text{RMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^n \left[\left(\frac{k}{k_0} \right)_i - \left(\frac{k}{k_0} \right)_i^* \right]^2} \quad (21)$$

where n represents the number of points, $(k/k_0)_i$ are experimental values, and $(k/k_0)_i^*$ are predicted values. The RMSE of $(k/k_0)_x$, $(k/k_0)_y$ and $(k/k_0)_z$ is 2.4E-2, 2.7E-2 and 3.6E-2, respectively. This verification demonstrates the accuracy and the applicability of the proposed model.

The detailed relationship between the effective coefficient and the effective principal stress increment is shown in Fig. 14. It is noteworthy that the loading path adopted in this study is characterized by a constant hydrostatic pressure ($\sigma_1 + \sigma_2 + \sigma_3$). Based on the permeability data analyzed in this study, the coefficients defined in this model are only capable of indicating their relative magnitudes and do not reflect their absolute values. Furthermore, the adopted stress paths indicate that each stress state involves changes in the principal stresses in only two directions relative to the hydrostatic stress state, with the

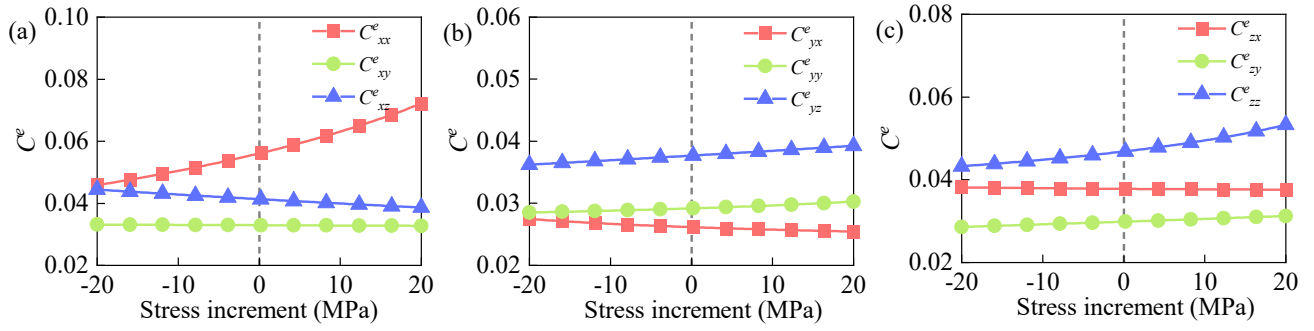


Fig. 14. Relationship between effective coefficients and effective principal stress increments, including (a) x -directional permeability, (b) y -directional permeability, and (c) z -directional permeability.

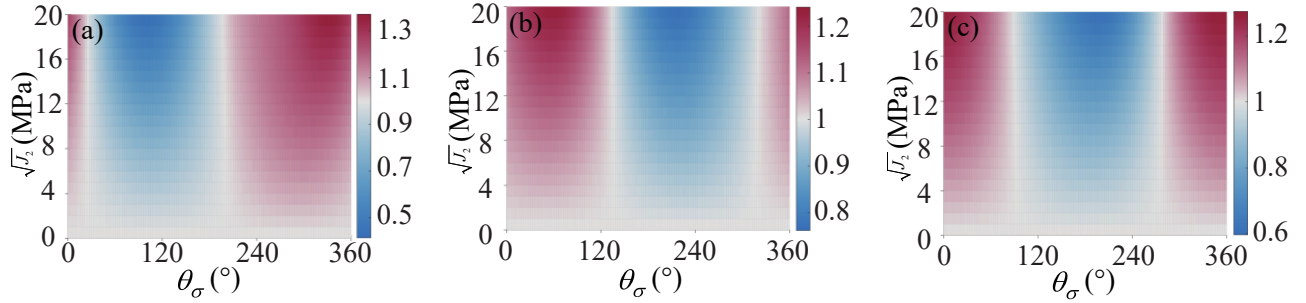


Fig. 15. Relationship between normalized permeability, deviatoric stress and Lode angle based on the theoretical model, including (a) x -directional permeability, (b) y -directional permeability, and (c) z -directional permeability.

two changes occurring in opposite directions ($\Delta\sigma_i = -\Delta\sigma_j = \Delta\sigma^e$). Substituting the above conditions into the permeability model yields $k = k^0 \exp[(C_j^e - C_i^e)\Delta\sigma^e]$, further indicating that the coefficients in the model reflect their relative magnitudes.

The larger the value of C^e is, the greater the dependence of permeability on the effective principal stress in that direction. For k_x , these effective coefficients are ranked in the following order: $C_{xx}^e > C_{xz}^e > C_{xy}^e$. Therefore, k_x exhibits the highest sensitivity to stress along the x -direction and the lowest sensitivity along the y -direction. For k_y , the condition $C_{yz}^e > C_{yy}^e > C_{yx}^e$ holds, indicating that k_y demonstrates the highest sensitivity to stress along the z -direction and the lowest sensitivity along the x -direction. For k_z , the condition $C_{zz}^e > C_{zx}^e > C_{zy}^e$ holds, indicating that k_z shows the highest sensitivity to stress along the z -direction and the lowest sensitivity along the y -direction. These sensitivity differences are consistent with the discussions presented in the previous sections. The permeability rises when the increase due to unloading of the effective principal stress exceeds the decrease caused by loading, and vice versa. Consequently, the Lode angle dependence of permeability reflects the differences in stress sensitivity. Moreover, a stronger Lode angle dependence indicates a greater difference in stress sensitivity.

The permeability of purple sandstone along the three principal directions was evaluated under various Lode angles and deviatoric stress levels. Subsequently, a theoretical model was employed to describe the permeability evolution and quantify its stress sensitivity. Based on the theoretical model, the permeability evolution under other stress states is further

discussed. The relationship between normalized permeability, deviatoric stress and Lode angle based on the theoretical model is shown in Fig. 15. First, $\theta_\sigma = 0^\circ$ and $\theta_\sigma = 360^\circ$ correspond to the same stress state. Regardless of the permeability direction, the variation exhibits a positive correlation with deviatoric stress, indicating that a higher deviatoric stress leads to more pronounced permeability changes. For $(k/k_0)_x$, its value remains close to 1 around the conditions of $\theta_\sigma = 25^\circ$ and $\theta_\sigma = 300^\circ$. The relationship of $(k/k_0)_x < 1$ holds between the $\theta_\sigma = 25^\circ$ and $\theta_\sigma = 300^\circ$ conditions, whereas $(k/k_0)_x > 1$ governs the behavior in the other regions. Furthermore, it reaches its minimum value near $\theta_\sigma = 100^\circ$ and its maximum value near $\theta_\sigma = 330^\circ$. For $(k/k_0)_y$, its value remains close to 1 around the conditions of $\theta_\sigma = 135^\circ$ and $\theta_\sigma = 320^\circ$. The relationship of $(k/k_0)_y < 1$ applies between the $\theta_\sigma = 135^\circ$ and $\theta_\sigma = 320^\circ$ conditions, whereas $(k/k_0)_y > 1$ dominates in the remaining regions. Furthermore, $(k/k_0)_y$ attains its maximum value near $\theta_\sigma = 60^\circ$ and its minimum value near $\theta_\sigma = 210^\circ$. For $(k/k_0)_z$, $(k/k_0)_z = 1$ is observed around the conditions of $\theta_\sigma = 90^\circ$ and $\theta_\sigma = 280^\circ$. The relationship of $(k/k_0)_z < 1$ holds under the condition of $\theta_\sigma \in (90^\circ, 280^\circ)$, whereas $(k/k_0)_z > 1$ governs the behavior in other regions. Furthermore, the minimum and maximum values of $(k/k_0)_z$ appear near $\theta_\sigma = 200^\circ$ and $\theta_\sigma = 360^\circ$, respectively.

The relationship between normalized permeability ratio, deviatoric stress and Lode angle based on the theoretical model is shown in Fig. 16. Similar to normalized permeability, the variation in normalized permeability ratio is also positively correlated with deviatoric stress. Around the conditions of

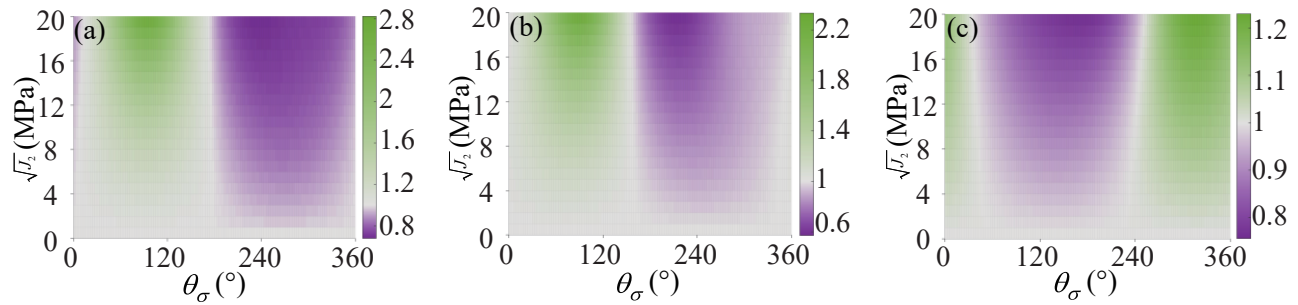


Fig. 16. Relationship between normalized permeability ratio, deviatoric stress and Lode angle based on the theoretical model, including: (a) $(k/k_0)_y/(k/k_0)_x$, (b) $(k/k_0)_z/(k/k_0)_x$ and (c) $(k/k_0)_z/(k/k_0)_y$.

$\theta_\sigma = 10^\circ$ and $\theta_\sigma = 180^\circ$, the value of $(k/k_0)_y/(k/k_0)_x$ remains equal to 1, indicating that the three-directional permeabilities exhibit similar variations relative to their initial permeabilities. For $(k/k_0)_z/(k/k_0)_x$, the corresponding conditions occur near $\theta_\sigma = 160^\circ$ and $\theta_\sigma = 360^\circ$, while those for $(k/k_0)_z/(k/k_0)_y$ occur near $\theta_\sigma = 40^\circ$ and $\theta_\sigma = 240^\circ$. $(k/k_0)_y/(k/k_0)_x > 1$ holds under the condition of $\theta_\sigma \in (10^\circ, 180^\circ)$, indicating that the increase in the former permeability relative to its initial value is greater than that of the latter. For $(k/k_0)_z/(k/k_0)_x$, the corresponding conditions holds at $\theta_\sigma \in (0^\circ, 160^\circ)$, while those for $(k/k_0)_z/(k/k_0)_y$ holds at $\theta_\sigma \in (240^\circ, 40^\circ)$. In the remaining regions, the opposite relationship is observed, suggesting a smaller increase in the former permeability relative to its initial value. Besides, the maximum and minimum values of $(k/k_0)_y/(k/k_0)_x$, $(k/k_0)_z/(k/k_0)_x$ and $(k/k_0)_z/(k/k_0)_y$ appear near $\theta_\sigma = 90^\circ/230^\circ$, $\theta_\sigma = 100^\circ/210^\circ$, and $\theta_\sigma = 320^\circ/180^\circ$, respectively.

The present study used laboratory experiments and theoretical modeling to investigate how the Lode angle affects directional permeability in purple sandstone at room temperature using dry helium flow. The experiments consisted of apparent permeability measurements under constant gas pressure, and the resulting data were interpreted and further discussed using the proposed theoretical model. No corresponding three-dimensional numerical simulations of oil and gas extraction were conducted. Besides, the stress paths adopted in the experiments were specifically designed to reveal the Lode angle dependence and do not represent the actual *in-situ* stress variations encountered during oil and gas extraction. Therefore, this study primarily focused on the fundamental characteristics of rock permeability. To provide more direct guidance for engineering applications, future work will perform further experiments and numerical simulations along actual *in-situ* stress evolution paths encountered during oil and gas extraction, as well as on a wider range of rock types.

5. Conclusions

In this study, a self-developed true-triaxial permeability testing system was introduced, which is capable of measuring permeability in three principal directions. To investigate the Lode angle dependence of permeability along the three principal directions, loading paths with constant hydrostatic pressure were adopted, incorporating four deviatoric stress levels (5, 10,

15, 20 MPa) coupled with six Lode angle conditions (0° , 60° , 120° , 180° , 240° , 300°).

The three-directional permeability showed pronounced non-monotonic variations with increasing Lode angle, highlighting the significant role of Lode angle dependence. Specifically, k_x and k_z underwent a decrease followed by an increase, while k_y demonstrated an increasing-decreasing-increasing variation. Moreover, the magnitude of permeability variation with Lode angle increased with rising deviatoric stress. The directional anisotropy of permeability was characterized using the following anisotropy ratios: k_y/k_x , k_z/k_x and k_z/k_y . Owing to intrinsic heterogeneity, anisotropy was observed in the three-directional permeabilities even under hydrostatic pressure conditions. The relative magnitudes among the three-directional permeabilities were found to alternate under varying deviatoric stress and Lode angle conditions, and the anisotropy variations with Lode angle became more pronounced as the deviatoric stress increased.

This study proposes a effective model for permeability along the three principal directions that characterizes its dependence on the Lode angle. The coefficients in the proposed model can accurately describe the discrepancy in permeability sensitivity to the individual effective principal stresses. This difference is reflected by the Lode angle dependence; a greater Lode angle dependence indicates a greater difference in stress sensitivity. When permeability is more sensitive in the loading direction than in the unloading direction, it decreases as the principal stress differences increase. Meanwhile, the opposite trend occurs when permeability is less sensitive in the loading direction.

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Conflicts of interest

The authors declare no competing interest.

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