

Article

Mechanical Behaviour and Flow Characteristics of Reservoir Sandstone Under Deep Triaxial Stress Conditions

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Abstract

The development of deep oil and gas reservoirs has become a key focus in the exploration and exploitation of hydrocarbon resources. To elucidate the mechanisms governing the flow evolution of reservoir sandstone under deep, high-triaxial stress conditions, this study takes the deep reservoir sandstone of a specific block as its subject. Using a true triaxial rock mechanics–seepage coupled testing system to simulate the in situ high-triaxial stress environment. Synchronous testing of the sandstone’s mechanical and seepage properties was conducted, and a staged permeability model for the elastic and damaged zones of the sandstone was developed and experimentally validated. The results indicate that, under deep, high-triaxial stress conditions, the total stress–strain behaviour of sandstone is divided into compaction, elastic deformation, yield and post-failure stages. The mechanical behaviour exhibits a ‘compression–unloading–failure’ pattern, whilst permeability follows a U-shaped evolution characterised by an ‘exponential decline–sudden increase–stabilisation’ trend; furthermore, the influence of damage on flow properties is irreversible. The intermediate principal stress exerts a significant strengthening effect on the mechanical properties of sandstone; as it increases, the peak strength and residual strength of the sandstone rise, whilst post-peak brittleness decreases and ductility increases. The intermediate principal stress is a key factor regulating the evolution of permeability. During the elastic stage, the initial permeability of the sandstone decreases as the stress increases, and the rate of exponential decay accelerates; during the damage stage, the post-peak permeability decreases as the stress increases, and the irreversible closure of pores caused by true triaxial stress makes it difficult for the post-peak permeability to recover to its initial value. The coefficient of determination for the permeability model fitted to the elastic stage is greater than 0.9, whilst that for the damage stage ranges from 0.76 to 0.85. These models effectively characterise the quantitative relationship between permeability and strain under different stress conditions, demonstrating good reliability and applicability. The research findings provide experimental evidence for elucidating the coupled relationship between mechanics and flow in sandstone under deep, high-triaxial stress conditions, as well as for predicting flow behaviour in deep reservoirs and designing development schemes.

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Keywords: deep reservoirs; sandstone; true triaxial stress; damage evolution; permeability model

1. Introduction

The development of deep oil and gas reservoirs is a key focus in current oil and gas exploration and production. Deep formations are generally characterised by high-triaxial stress environments, under which the mechanical and flow properties of reservoir sandstones undergo significant changes, directly affecting the extraction efficiency of oil and gas reservoirs and the design of development schemes. As the primary lithological type of deep reservoirs, the pore structure and microfracture development of sandstone are significantly regulated by triaxial stress. Changes in the stress field can trigger a series of mechanical behaviours in the rock, such as compaction, damage and fracturing, which in turn lead to dynamic evolution of permeability. Clarifying the coupling relationship between these two factors is of great significance for the study of flow patterns in deep reservoirs [1–6].

In fields such as deep resource extraction, oil and gas reservoir development, and the stability assessment of underground engineering projects, rock flow characteristics are one of the core factors determining engineering safety and resource extraction efficiency. In their actual in situ environments, rocks are generally subjected to three-dimensional principal stresses of unequal magnitude ($\sigma_1 > \sigma_2 > \sigma_3$), and the mechanisms by which flow behaviour is regulated by stress states are extremely complex. Conventional triaxial tests ($\sigma_2 = \sigma_3$), which simplify the stress conditions, have long been the primary method for studying rock flow. In contrast, true triaxial tests ($\sigma_1 > \sigma_2 > \sigma_3$) can more accurately simulate the in situ stress environment of rock masses and have gradually become a key technique for elucidating flow mechanisms under complex stress conditions in recent years [7,8]. Conventional triaxial seepage tests, which simulate lateral confinement in rock by applying equal confining pressures ($\sigma_2 = \sigma_3$), have yielded a wealth of fundamental data in the study of rock seepage characteristics. Early research primarily focused on the relationship between stress levels and permeability. Zoback et al. [9] found through conventional triaxial tests that high-pressure deformation significantly reduces sandstone permeability, confirming the dominant role of stress-induced pore compression and fracture closure. With the development of testing techniques, researchers have begun to focus on complex conditions such as cyclic loading and rock–water coupling. Mitchell et al. [10] revealed the correlation between cumulative damage and permeability hysteresis effects through conventional triaxial cyclic loading tests on granite and granodiorite. Chen et al. [11] combined X-ray computed tomography (CT) technology to analyse the intrinsic relationship between damage evolution and permeability changes in granite under conventional triaxial compression, proposing that damage accumulation is the core mechanism driving permeability growth. In the fields of oil, gas and coalbed methane development, conventional triaxial flow tests provide key parameters for reservoir evaluation. Ranjith et al. [12] developed a specialised triaxial apparatus and systematically studied the evolution of permeability in coal rock during CO₂ sequestration. Liu et al. [13] established a time-evolution model of coal permeability under conventional triaxial stress, quantifying the coupled effects of effective stress, gas desorption and matrix shrinkage. Researchers have also conducted targeted studies on different rock types. Wang et al. [14] established a predictive model for the permeability of laminated shale in relation to water content and bedding angle using conventional triaxial tests. Liu et al. [15] revealed the development characteristics of stress-induced permeability anisotropy in porous sandstone under conventional triaxial compression. However, conventional triaxial tests fail to reflect the complex stress

state of actual rock masses as they neglect the independent effect of the intermediate principal stress (σ_2). A large body of in situ stress monitoring data indicates that the differences between the three principal stresses increase significantly with depth [16,17], and the flow patterns derived from conventional triaxial tests deviate from engineering reality.

True triaxial tests, by independently applying three unequal principal stresses, can reproduce the anisotropic characteristics of in situ rock stresses, thereby providing technical support for elucidating the regulatory mechanism of the intermediate principal stress on seepage. Since Mogi [18] designed the first true triaxial testing apparatus for rock and discovered the significant influence of σ_2 on rock strength and deformation, the technology of true triaxial seepage testing has gradually developed and improved. Sato et al. [19] upgraded the Mogi-type true triaxial apparatus by adding permeability measurement lines in the σ_1 and σ_2 directions, thereby achieving the simultaneous testing of bidirectional permeability for the first time. They discovered that the permeability anisotropy of Berea sandstone is closely related to the intermediate principal stress, and that the formation of fault mud under high- σ_2 conditions significantly reduces permeability in the σ_1 direction. In terms of experimental apparatus development, researchers have continually overcome technical bottlenecks. Li et al. [20] developed a multifunctional true triaxial geophysical apparatus capable of precisely controlling 3D stress (up to 6000 kN) and fluid pressure (up to 60 MPa). It enables continuous monitoring of stress, displacement, flow rate and acoustic emission signals, providing an integrated solution for studies on the coupling of flow, stress and damage. The true triaxial geomechanical imaging system developed by the University of Toronto [16] employs a unique three-way sealing technology to enable the simultaneous measurement of 3D permeability and parameters such as ultrasonic waves and acoustic emission during rock fracturing. The advent of these devices has significantly expanded the scope of application for true triaxial flow tests, covering a wide range of rock types—including hard rock, shale and coal—as well as complex operating conditions such as high temperature and high pressure. Regarding the study of permeability behaviour, numerous experiments have confirmed that the intermediate principal stress is a key factor in regulating permeability. Li et al. [20] found through true triaxial seepage tests on shale that, at a gas pressure of 4 MPa, as σ_1 , σ_2 and σ_3 increased from 10 MPa to 60 MPa, the permeability decreased by 62.62%, 91.02% and 37.40%, respectively, confirming that σ_2 exerts the most significant inhibitory effect on seepage. Xie et al. [16] pointed out in their review study that the response of rock permeability to the three principal stresses exhibits significant differences, and that the formation and distribution of fractures are markedly dependent on the principal stresses, with the intermediate principal stress regulating fluid migration pathways by constraining the direction of fracture propagation. For rocks containing weak structural planes, Sato et al. [19] found that the coupling relationship between structures such as bedding and joints and the direction of stress further exacerbates permeability anisotropy, whilst variations in σ_2 under true triaxial conditions alter the degree of closure and shear slip characteristics of structural planes, thereby restructuring the flow pathways.

Existing studies on the flow characteristics of rocks are predominantly based on conventional triaxial stress conditions, which differ significantly from the actual true triaxial high-stress environment found in deep geological formations. The influence of the intermediate principal stress on the mechanical and flow behaviour of sandstone has not yet been fully elucidated, and there is a lack of mathematical models capable of accurately characterising the differentiated dynamic evolution of permeability during the elastic and damage stages under deep high-stress conditions. Consequently, it is difficult to meet the requirements for accurately predicting flow behaviour in deep oil and gas reservoirs. In response to these research shortcomings, this paper proposes a core scientific hypothesis: under deep, true triaxial high-stress conditions, the intermediate principal stress σ_2 is the

key factor controlling the full stress–strain mechanical response of sandstone and governing the dynamic evolution of permeability. Different levels of σ_2 alter the compaction, expansion and interconnection characteristics of pores and fractures within the rock mass, resulting in distinct flow evolution patterns between the elastic and damage stages of sandstone. Based on this, this paper takes sandstone as the subject of study and employs a true triaxial mechanical–seepage coupled testing system to simulate a deep, high-stress environment at a burial depth of 3000 m. Synchronous mechanical and seepage tests were conducted with the aim of elucidating the mechanisms of mechanical–seepage coupling in sandstone under the influence of the intermediate principal stress, and establishing a staged permeability–evolution model for sandstone suited to deep, high-stress environments, thereby providing theoretical support and experimental evidence for seepage prediction and the efficient development of deep oil and gas reservoirs.

2. Study on the Flow Characteristics of Reservoir Sandstone Under Deep High Triaxial Stress

2.1. Experimental Protocol

2.1.1. Rock Sample Preparation and Testing of Basic Physical Properties

Sandstone core samples were collected from deep reservoir strata in a specific block. Subsequently, in accordance with the guidelines recommended by the International Society for Rock Mechanics (ISRM), the sandstone core samples were cut into prismatic specimens measuring 50 mm × 50 mm × 100 mm and polished [21,22]. The test specimens for this experiment are shown in Figure 1. All specimens were dried in a drying oven to eliminate the influence of pore water on the mechanical and permeability properties of the rock. Three rock samples were selected and numbered sequentially as A-1-1, A-1-2 and A-1-3. Physical property tests were carried out using a rock permeability testing system and an ultrasonic analyser to determine basic physical parameters such as the initial permeability, bulk density and P-wave velocity of the samples. Based on the measured data, mechanical parameters such as the modulus of elasticity and Poisson’s ratio were further calculated. All test and calculation results are shown in Table 1 [23,24].



Figure 1. Sandstone specimens.

Table 1. Parameters relating to sandstone specimens.

	Initial Permeability (mD)	P-Wave Velocity (m/s)	S-Wave Velocity (m/s)	Bulk Density (g/cm ³)	Dynamic Young’s Modulus (GPa)	Dynamic Poisson’s Ratio (Dimensionless)
A-1-1	2.83397	1355.67	869.67	2.45	4.27	0.15
A-1-2	1.5385	1430	914.33	2.46	4.761	0.15
A-1-3	0.4491	1387	899.67	2.46	4.53	0.14

2.1.2. Test Equipment and Loading Protocol

The tests utilised a true triaxial rock mechanics–seepage coupled testing system, which is capable of independently controlling the three principal stresses (σ_1 , σ_2 , σ_3) and pore pressure to simulate a deep, in situ, high-triaxial stress environment. The loading scheme was designed based on the in situ stress distribution in the study area: first, the minimum principal stress (σ_3) and the intermediate principal stress (σ_2) were applied at a constant rate to their target values, followed by the gradual application of the maximum principal stress (σ_1) until specimen failure. Permeability was measured synchronously during the stress loading process to investigate the irreversible deformation and seepage characteristics of the sandstone. The stress loading scheme and seepage direction are shown in Figure 2 and Table 2.

In this study, CO₂ was used as the flow fluid for permeability testing using the transient pressure pulse method. Prior to testing, the rock sample was placed in a holder, and CO₂ was introduced into the upstream and downstream sections of the flow system to achieve pore saturation. The test employed unidirectional flow along the direction of the intermediate principal stress. To simulate the reservoir's pore pressure of 70 MPa (p_p), a differential pressure of 10 MPa was established for permeability measurement, with the upstream inlet pressure maintained at a constant 10 MPa, whilst the downstream outlet was at atmospheric pressure, thereby establishing a stable pressure gradient along the specimen's principal stress direction. The entire test was conducted at room temperature, with the test deemed to have stabilised once the upstream and downstream gas pressures were fully balanced and the pressure readings showed no significant fluctuations. The specimens were encased in fluorocarbon rubber sleeves and placed within a triaxial holder, where confining pressure was applied to ensure sealing of the sidewalls and end faces, thereby eliminating interference from fluid bypass; the gas permeability was calculated using the modified Ward–Maksimovic model, with the following formula [25]:

$$k = \frac{\mu L V_u V_d}{A \Delta P_0 (V_u + V_d)} \cdot \frac{\ln \left(\frac{\Delta P_1}{\Delta P_2} \right)}{\Delta t} \quad (1)$$

where k is the gas permeability of the rock sample, m²; μ is the dynamic viscosity of CO₂ at room temperature, Pa·s; L is the flow length of the rock sample, m; A is the cross-sectional area of the rock sample, m²; V_u is the volume of the upstream gas reservoir, m³; V_d is the volume of the downstream gas reservoir, m³; ΔP_0 is the initial pressure difference between upstream and downstream, Pa; ΔP_1 is the instantaneous pressure difference at the start of the test, Pa; ΔP_2 is the instantaneous pressure difference at the end of the test, Pa; Δt is the duration of pressure difference decay, s.

Table 2. Three-dimensional stress states under each test stage.

	σ_3 (MPa)	σ_2 (MPa)	σ_1 (MPa)
Condition 1	80	80, 90, 100	80, 90, 100, 110, 120, 130, 140...

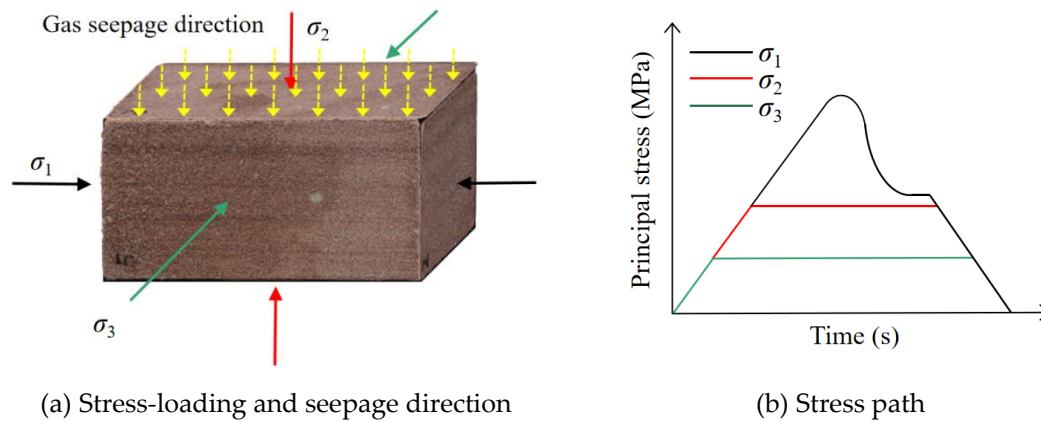


Figure 2. Schematic of true triaxial test plans.

2.2. Permeability Model

Model assumptions: a. horizontal isotropy; b. the effect of gas adsorption can be neglected; c. constant temperature (the effect of temperature is neglected).

2.2.1. Permeability Models for the Elastic Zone of Rock

For porous media, permeability depends on the level of porosity [26].

$$\varphi_p = \frac{V_p}{V} = \frac{V_{p0} + \Delta V_p}{V_0 + \Delta V} \varphi_{p0} = \frac{V_{p0}}{V_0} \quad (2)$$

$$\varepsilon_v = \frac{\Delta V}{V_0} \varepsilon_p = \frac{\Delta V_p}{V_{p0}} \quad (3)$$

where φ_p is the porosity of the samples at the current state, φ_{p0} is the porosity of the samples at the initial state, V_{p0} and V_0 are the initial volumes of the pores and rock, m^3 , respectively, and ΔV and ΔV_p are the volume changes in the rock and pores, m^3 , respectively. Under Darcy's law, permeability and porosity are related as follows [27]:

$$\frac{k_f}{k_{0f}} = \left(\frac{\varphi_p}{\varphi_{p0}} \right)^3 \left(\frac{1 - \varphi_{p0}}{1 - \varphi_p} \right)^2 \quad (4)$$

A great deal of experimental data indicates that $\varphi_p \ll 1$; therefore, it can be obtained from Equation (4) [28,29]:

$$\frac{k_f}{k_{0f}} = \left(\frac{\varphi_p}{\varphi_{p0}} \right)^3 \quad (5)$$

Taking the change in porosity as the characteristic parameter reflecting the change in the permeability coefficient, the differential form of Equation (2) is [30]:

$$d\varphi_p = d \left(\frac{V_p}{V} \right) = \frac{V_p}{V} (d\varepsilon_v - d\varepsilon_p) \quad (6)$$

$$d\varepsilon_v = -\frac{1}{K} (d\sigma_i - \alpha_v dp) \quad (7)$$

$$d\varepsilon_p = -\frac{1}{K_p}(d\sigma_i - \alpha_p dp) \quad (8)$$

where K is the bulk modulus of the sandstone, $K = E/(3(1 - 2\nu))$, Pa; E is the Young's modulus of the sandstone specimens, Pa; ν is Poisson's ratio; α is Biot's coefficient; $i = 1, 2, 3$.

To account for the effect of effective volumetric strain on porosity, Equations (7) and (8) are substituted into Equation (6):

$$\frac{d\varphi_p}{\varphi_p} = d\varepsilon_v - d\varepsilon_p = \left(\frac{1}{K} - \frac{1}{K_p} \right) (d\sigma_x + d\sigma_y + d\sigma_z - 3dp) \quad (9)$$

Given the poor adsorption of dense rock masses, the adsorption effect is often disregarded, and the volume change in porous media follows the Betti–Maxwell reciprocity theorem:

$$K_p = \frac{\varphi_p}{\alpha} K \quad (10)$$

Combining Equations (6)–(10) with Equation (4) yields:

$$\frac{k_f}{k_{0f}} = \exp \left[\Delta\sigma \frac{1}{K} \left(1 - \frac{\alpha}{\varphi_p} \right) \right] = \exp \left[3(1 - 2\nu) \Delta\varepsilon_v \left(1 - \frac{\alpha}{\varphi_p} \right) \right] \quad (11)$$

2.2.2. Permeability Model for Damaged Rock Sections

With regard to the damage variable D , this is an internal variable describing the stress–strain changes and the degradation of mechanical properties within sandstone. According to Kachanov's definition of damage, the damage of a material can generally be expressed as the ratio of the number of damaged elements N_f to the total number of elements N , i.e.,

$$D = \frac{N_f}{N} \quad (12)$$

The Weibull distribution function is used to describe the random statistical distribution law of rock microelement strength, and $P[F]$ can be expressed by the following equation [22,31,32]:

$$P[F] = \frac{n}{F_0} \cdot \left(\frac{F}{F_0} \right)^{n-1} \exp \left[-\left(\frac{F}{F_0} \right)^n \right] \quad (13)$$

where n is the characteristic parameter of the Weibull distribution, and F_0 is the scale parameter, Pa. Substituting Equation (13) into Equation (12) yields:

$$D = 1 - \exp \left[-\left(\frac{F}{F_0} \right)^n \right] \quad (14)$$

Based on J. Lemaitre's strain equivalence principle, the damage constitutive relationship of rock is as follows:

$$\sigma = \sigma_e (1 - D) = E\varepsilon (1 - D) \sigma_{ei} = \frac{E_i \varepsilon_i \sigma_i}{\sigma_1 - \nu(\sigma_2 + \sigma_3)} \quad (15)$$

where σ is the nominal stress, Pa; σ_e is the effective stress, Pa; hence, σ_v can be expressed as:

$$d\sigma_v = \frac{d\sigma_x + d\sigma_y + d\sigma_z - 3dp}{1 - D} \quad (16)$$

The Drucker–Prager criterion (D–P criterion) is widely used in the field of geotechnical engineering due to its consideration of the influence of intermediate principal stresses on rock damage and deformation characteristics, and it is expressed as follows [33]:

$$\begin{cases} f = \sqrt{J_2} - \alpha I_1 - k = 0 \\ J_2 = \frac{1}{6} \left[(\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2 \right] \\ I_1 = \sigma_1 + \sigma_2 + \sigma_3 \end{cases} \quad (17)$$

where α is a characteristic parameter in the D–P criterion; hence, we get the following equation:

$$F = f(\sigma_e) = \sqrt{J_2} - \alpha I_1 \quad (18)$$

The key to establishing the damage constitutive relationship lies in determining the Weibull distribution parameter n and the scale parameter F_0 ; these parameters can be obtained by solving the two boundary conditions of the stress–strain curve: ① geometric conditions and ② boundary conditions:

$$n = \frac{-F_p}{\varepsilon_p \left. \frac{\partial F}{\partial \varepsilon_1} \right|_{\varepsilon_1 = \varepsilon_p} \ln \left\{ \frac{\sigma_p - \nu(\sigma_2 + \sigma_3)}{E\varepsilon_p} \right\}} \quad (19)$$

$$F_0 = \frac{F_p}{\left\{ -\ln \left[\frac{\sigma_p - \nu(\sigma_2 + \sigma_3)}{E\varepsilon_p} \right] \right\}^{\frac{1}{n}}} \quad (20)$$

where σ_p is the peak stress, Pa; ε_p is the peak strain. Combining Equations (16)–(20) with Equation (11) yields and adds the joint surface degradation parameter C to the penetration model. The permeability coefficient expression of the rock mass under damage conditions can be expressed as

$$\frac{k_f}{k_{0f}} = \exp \left\{ \frac{3(1 - 2\nu)\Delta\varepsilon_v \left(1 - \frac{\alpha}{\varphi_p} \right)}{\exp \left[-\left(\frac{F}{F_0} \right)^n \right]} \right\} + C \quad (21)$$

3. Results

3.1. Mechanical and Hydraulic Properties of Sandstone Under Deep Triaxial Stress

The deformation and failure behaviour of rock under triaxial stress conditions are closely related to its mechanical properties and have a significant influence on the permeability characteristics of sandstone specimens; therefore, analysing the correlation between rock fracture and permeability evolution under the influence of underground min-

ing stresses is of great importance. Figure 3 shows the total stress–strain curve for sandstone under a minimum principal stress (σ_3) of 80 MPa. As can be seen from Figure 3, the deformation of sandstone during the total stress–strain process, as it evolves with the characteristic stress threshold, can be divided into a consolidation stage, an elastic deformation stage, a yield stage and a post-failure stage [34,35]. Under conditions of constant minimum principal stress (σ_3), as the intermediate principal stress (σ_2) increased from 80 MPa to 100 MPa, the peak strength of the specimen rose significantly, demonstrating a pronounced intermediate principal stress strengthening effect. Throughout the deformation process, the rock exhibited a three-stage mechanical behaviour of ‘compression–unloading and expansion–failure’, whilst the permeability correspondingly followed a U-shaped evolution pattern of ‘exponential decline–sudden increase–stabilisation’. The initial permeability and the minimum permeability decrease as the intermediate principal stress (σ_2) increases, indicating that a higher intermediate principal stress (σ_2) further compacts the pores and inhibits the opening of microcracks, resulting in more thorough compaction of the rock. Initial compaction stage: The intermediate principal stress (σ_2) and minimum principal stress (σ_3) stabilise rapidly, whilst the maximum principal stress (σ_1) rises linearly, the rock is progressively compacted, the voids close, and the corresponding permeability continues to decrease. Peak and damage stage: After the maximum principal stress (σ_1) reaches its peak, it drops rapidly; microcracks proliferate and propagate extensively, the rock enters a volume expansion phase, and the permeability begins to rise slowly after reaching its lowest point. Stable failure stage: The maximum principal stress (σ_1) remains at a plateau value; cracks further penetrate to form macroscopic shear zones, and permeability continues to rise as flow pathways develop. Final unloading stage: The maximum principal stress (σ_1) linearly unloads to the initial stress conditions; that is, after stress release, permeability remains at a relatively high level, indicating that damage has an irreversible effect on the flow characteristics of sandstone. Furthermore, high intermediate principal stress (σ_2) inhibits the increase in permeability during the failure stage and limits the development of crack flow pathways; ultimately, this manifests as a higher proportion of post-failure permeability recovery to initial levels with increasing intermediate principal stress (σ_2). It is believed that the intermediate principal stress (σ_2) exerts a comprehensive effect on the strength and flow characteristics of sandstone specimens by controlling the evolution of damage and changes in pore structure [27,36].

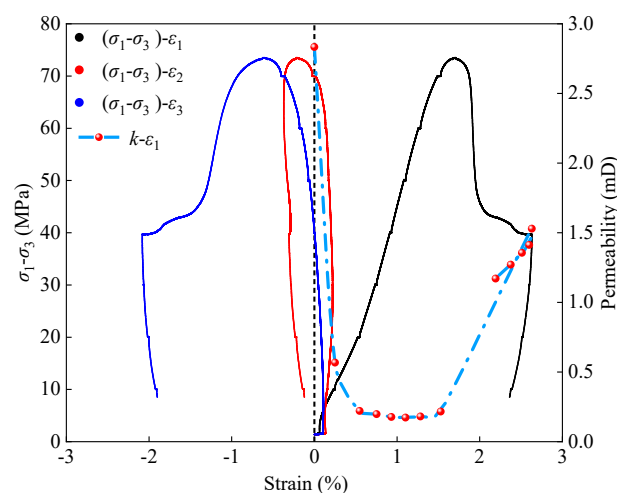
3.2. Model Validation

The two-stage permeability model summarised above was validated by fitting it to the following test dataset; the relevant parameters are shown in Table 3. As shown in Figure 4, during the elastic stage, the permeability of sandstone under all three true triaxial stress conditions exhibited an exponential decay trend with increasing strain, and the initial permeability was negatively correlated with the intermediate principal stress: the initial permeability of the specimen with low intermediate principal stress (A-1-1) was approximately 2.8 mD, and that of the specimen with medium intermediate principal stress (A-1-2) was approximately 1.5 mD, whilst the specimen with high principal stress (A-1-3) was approximately 0.4 mD; the rate of decay was likewise modulated by confining pressure, with lower principal stresses resulting in a faster decay. For the specimen with low principal stress, permeability had already fallen to around 20 per cent of its initial value at a strain of 0.5 per cent, whereas the specimen with high principal stress exhibited a more gradual decay. The coefficients of determination (R^2) for the fitted curves of the first three groups upon reaching peak strength were $R^2 = 0.92$, $R^2 = 0.95$ and $R^2 = 0.90$, respectively. This indicates that the model can characterise the quantitative relationship between permeability and strain with high accuracy, effectively validating the model’s reliability and the rationality of the experimental results, whilst also revealing that the intermediate

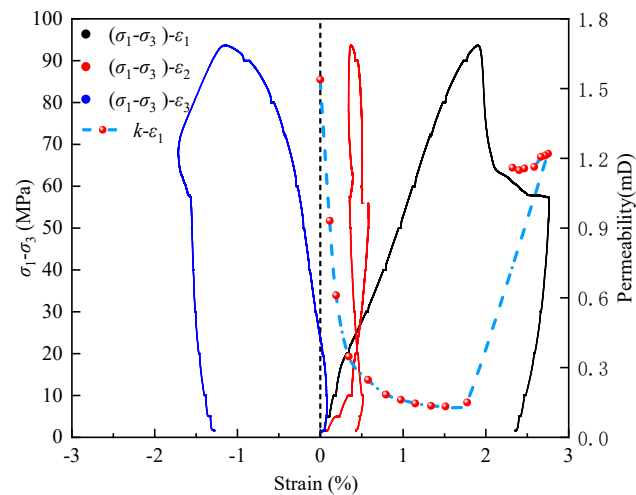
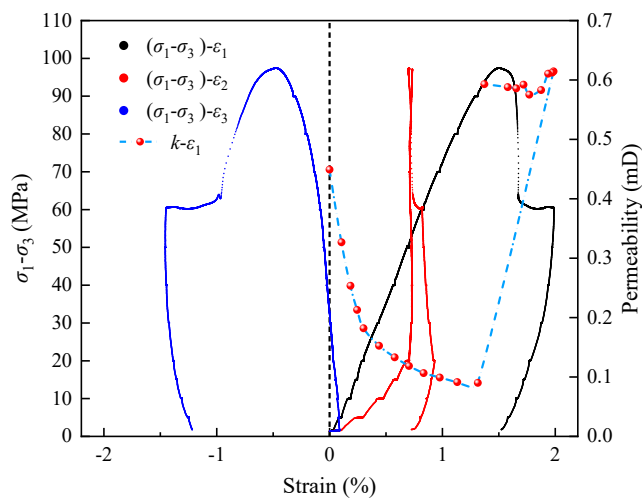
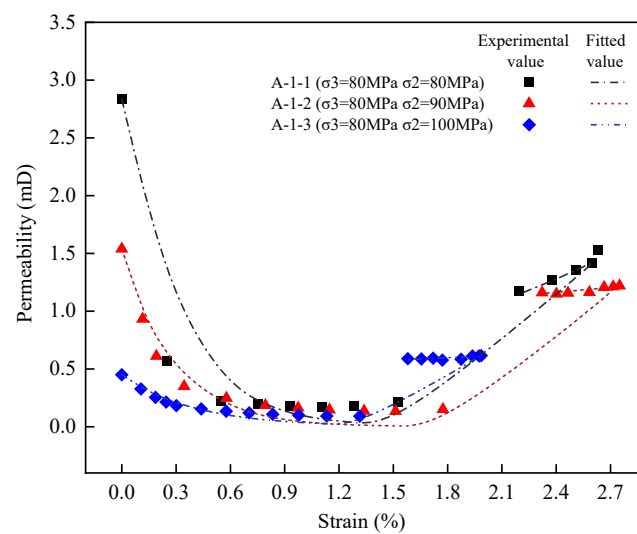
principal stress is a key factor influencing the initial permeability of sandstone and its permeability decay behaviour under strain-driven conditions. During the damage stage, the three sets of different intermediate principal stress conditions had a significant impact on the evolution of permeability. Post-peak permeability was the highest in the sample with high intermediate principal stress (A-1-3), followed by the sample with medium intermediate principal stress (A-1-2), and the lowest in the sample with low intermediate principal stress (A-1-1). The permeability of A-1-1 decreased from 1.55 mD to 1.2 mD, representing the greatest reduction of approximately 29%; the permeability of A-1-2 showed the second-largest reduction, decreasing from 1.2 mD to 1.15 mD, a reduction of approximately 4%; A-1-3 exhibited the smallest decrease in permeability, remaining stable within the range of 0.55–0.65 mD and varying gradually with strain. Furthermore, although permeability rose significantly after the peak, it struggled to return to its initial value; it is believed that true triaxial stress caused extensive pore closure, resulting in irreversible deformation of the pore structure. The experimental data points for permeability versus strain showed excellent agreement with the model-fitted curves, validating the reliability and applicability of the developed model within this stress range. The results indicate that the model can accurately characterise the evolution of rock permeability with strain under different stress conditions, providing a basis for the subsequent analysis of seepage characteristics.

Table 3. Parameter information.

Number	Elastic Stage				Damaged Stage				C
	Poisson's Ratio	Biot's Coefficient	Porosity	Goodness of Fit	Poisson's Ratio	Biot's Coefficient	Porosity	Goodness of Fit	
A-1-1	0.2	0.35	0.12	0.92	0.25	0.63	0.2	0.85	0.67
A-1-2	0.22	0.35	0.11	0.95	0.23	0.6	0.2	0.78	0.79
A-1-3	0.22	0.33	0.13	0.90	0.3	0.71	0.22	0.76	1.06



(a) A-1-1 ($\sigma_3 = 80$ MPa, $\sigma_2 = 80$ MPa)

(b) A-1-2 ($\sigma_3 = 80$ MPa, $\sigma_2 = 90$ MPa)(c) A-1-3 ($\sigma_3 = 80$ MPa, $\sigma_2 = 100$ MPa)**Figure 3.** Full stress–strain curve of sandstone.**Figure 4.** Permeability fitting curve.

4. Analysis and Discussion

4.1. The Controlling Influence of Deep High Triaxial Stress Conditions on the Mechanical Behaviour of Reservoir Sandstone

Figure 5 shows the stress–strain curves of sandstone under the control of the middle principal stress, from loading through failure to the residual deformation stage. The figure indicates that the regular variations in the stress–strain curves of the sandstone under the three stress conditions, as a function of the middle principal stress, are broadly consistent overall. Linear elastic stage ($\varepsilon < 1.0\%$): The slopes of the curves are similar, indicating that at low strain levels, the intermediate principal stress has a negligible effect on the rock's initial elastic stiffness, and the material deformation is predominantly elastic and reversible. Yield stage ($1.0\% < \varepsilon < \varepsilon_{\text{peak}}$): The slope of the curve gradually decreases, marking the transition to the plastic deformation stage. As the intermediate principal stress increases, the range of strain within the plastic strengthening stage expands, and the peak deviatoric stress rises significantly. Peak strength: Its order is high intermediate principal stress specimen (A-1-3) > medium intermediate principal stress specimen (A-1-2) > low intermediate principal stress specimen (A-1-1), indicating that the intermediate principal stress effectively enhances the rock's load-bearing limit by constraining lateral deformation and delaying the initiation and propagation of microcracks. Post-peak stage ($\varepsilon > \varepsilon_{\text{peak}}$): The post-peak stress decreases rapidly and tends to stabilise. As the intermediate principal stress increases, the residual strength follows the following order: high intermediate principal stress specimen (A-1-3) > medium intermediate principal stress specimen (A-1-2) > low intermediate principal stress specimen (A-1-1). Furthermore, the post-peak brittle characteristics increase whilst ductility diminishes. Under high- σ_2 conditions, this manifests as a brittle–ductile transition failure, whilst under moderate- σ_2 conditions, it manifests as ductile shear failure, reflecting the strengthening effect of the intermediate principal stress on the rock's post-peak load-bearing capacity [37,38].

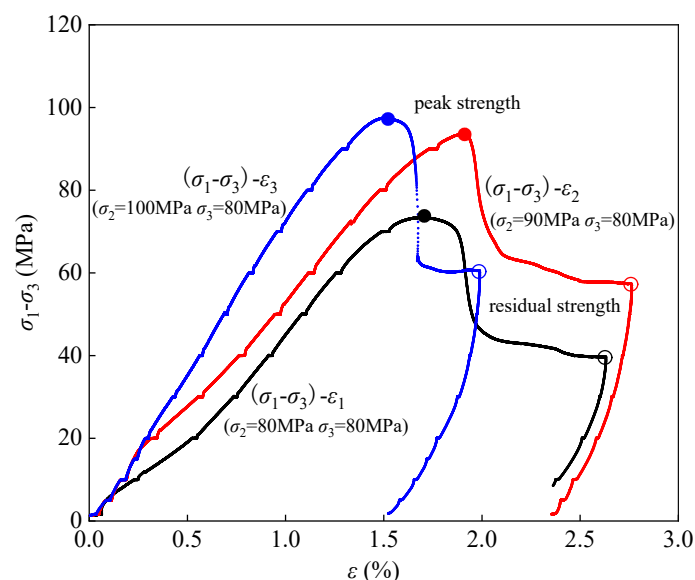
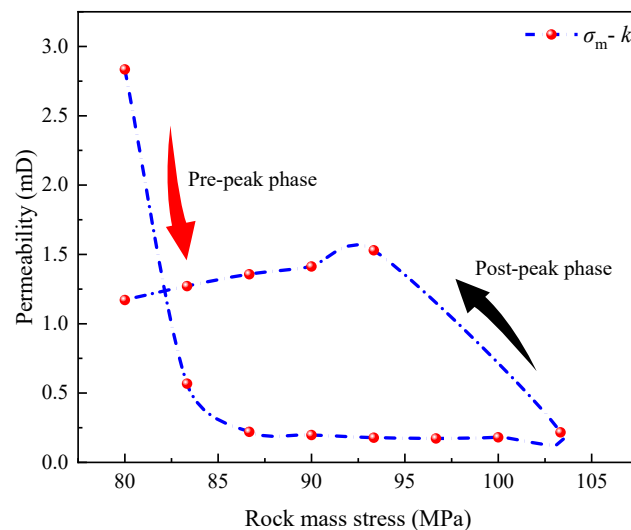


Figure 5. Stress–strain curves of sandstone under principal stress control.

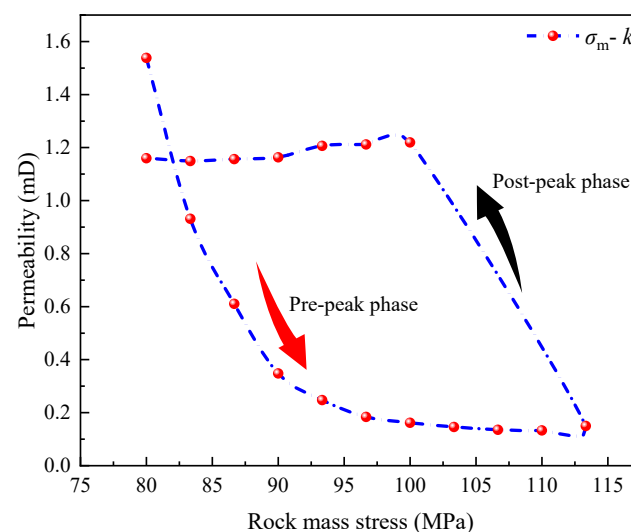
4.2. Comparative Analysis of Permeability Evolution Mechanisms in the Elastic–Plastic Stages

Based on the evolution of sandstone permeability with respect to characteristic stress thresholds during the total stress–strain process, the changes in permeability can be divided into four stages: Compaction and elastic stage: Pores within the sandstone are rapidly compacted, and permeability shows a rapid downward trend. Damage stage: Cracks

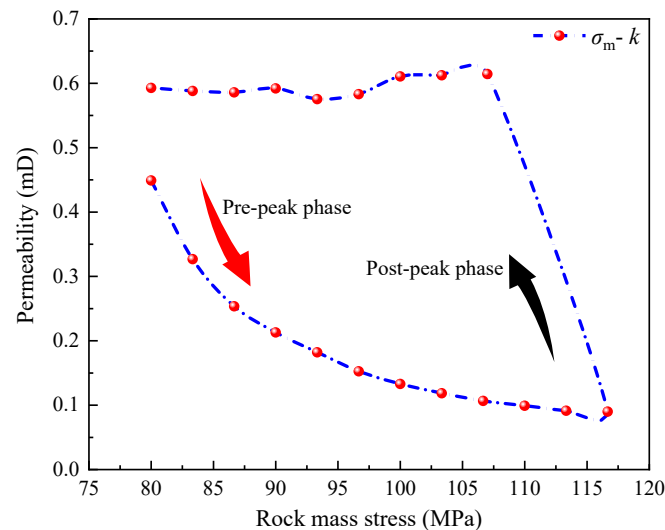
initiate and develop under the action of deviatoric stress; during this stage, permeability tends to stabilise. Peak stage: Cracks within the sandstone specimen develop in a non-stationary manner, and permeability slowly recovers due to the local opening of cracks. Post-peak stage: A macroscopic fracture network appears in the sandstone specimen, and permeability rapidly increases to the initial permeability level. The decreasing initial permeability in Figure 6, i.e., A-1-1 > A-1-2 > A-1-3, indicates that the increase in the intermediate principal stress exerts a suppressing effect on permeability; simultaneously, the permeability of the sandstone and the volume stress ($\sigma_m = (\sigma_1 + \sigma_2 + \sigma_3)/3$) exhibit a correlation. During the stress concentration phase, as rock mass stress gradually increases, internal pores and microfractures are continuously compressed and closed, resulting in a significant reduction in fluid flow pathways, manifested as a sharp decline in permeability, whereas upon entering the stress release phase, as stress is gradually relieved, the compressed and closed microfractures gradually reopen and expand, and flow pathways are progressively restored, causing permeability to first rise slowly and then increase rapidly, eventually approaching the initial level. Under equivalent volumetric stress conditions, the permeability of sandstone can increase by a factor of several dozen, and the σ_m - k relationship can, to a certain extent, reflect stress concentration and release in deep reservoir sandstones.



(a) A-1-1 ($\sigma_3 = 80$ MPa, $\sigma_2 = 80$ MPa)



(b) A-1-2 ($\sigma_3 = 80$ MPa, $\sigma_2 = 90$ MPa)



(c) A-1-3 ($\sigma_3 = 80$ MPa, $\sigma_2 = 100$ MPa)

Figure 6. Experimental results on the true triaxial fracture-seepage characteristics of deep reservoir sandstone.

4.3. Sensitivity of Permeability to Porosity

The fitted pore volume values are taken as reference values, and a 10% positive and negative perturbation is applied to generate new permeability values. The newly generated permeability values are compared with the baseline values, and the minimum and maximum relative errors are calculated. As shown in Figure 7, under three sets of different intermediate principal stress (σ_2) conditions (with the minimum principal stress σ_3 held constant at 80 MPa), the sensitivity of permeability to porosity in the elastic and damage stages of sandstone was assessed, and the sensitivity of permeability to porosity was quantified numerically through a comparison of relative errors. The results indicate that both the range and absolute values of relative errors in the elastic stage are significantly greater than those in the damage stage. This reflects that the sensitivity of permeability to porosity is characterised more accurately in the damage stage, whereas the dispersion of errors is higher in the elastic stage. Specifically, as σ_2 is gradually reduced from 100 MPa to 80 MPa, the negative deviation in the elastic stage increased from -0.167% to -0.377% , whilst the positive peak rose from 0.182% to 0.408% , demonstrating a trend of errors continuously increasing as the principal stress decreases. This indicates that the relationship between porosity and permeability is significantly more influenced by principal stress under conditions of low principal stress. The relative error in the damage stage consistently converges strictly within $\pm 0.07\%$, approaching zero ($\pm 0.004\%$) at $\sigma_2 = 90$ MPa, demonstrating high stability. This pattern reveals that, under true triaxial stress conditions, the sensitivity of porosity to permeability yields a far higher response accuracy in the damage stage than in the elastic stage, and that the intermediate principal stress has a more pronounced effect on the error in the porosity–permeability relationship during the elastic stage. The conclusions provide key evidence for the validation and optimisation of the porosity–permeability model under true triaxial stress conditions, whilst also indicating that, under conditions of low intermediate principal stress, particular attention can be paid to the influence of porosity evolution during the elastic stage on permeability.

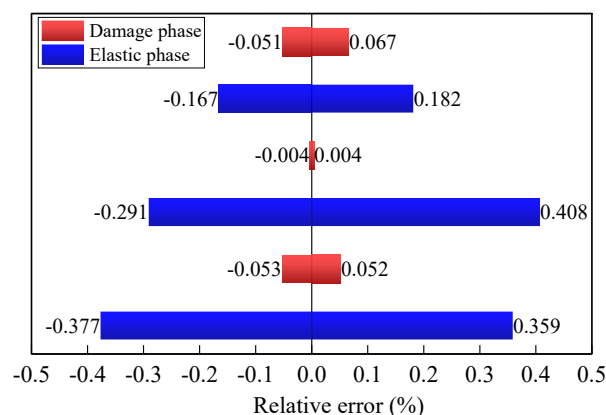


Figure 7. Analysis of the sensitivity of permeability to porosity under different intermediate principal stresses.

4.4. Influence of Stress Path on Seepage Characteristics

Figure 8 illustrates the influence of different intermediate principal stresses σ_2 on the evolution of permeability versus maximum principal strain in sandstone under the same minimum principal stress ($\sigma_3 = 80$ MPa). The experimental results indicate that the permeability of the sandstone generally exhibits a three-stage characteristic of ‘rapid decrease–stability at a low point–recovery after the peak’. As σ_2 increases, the brittleness of the sandstone increases, and the extent of permeability recovery after the peak is significantly enhanced. At $\sigma_2 = 80$ MPa, the sandstone exhibits ductile failure, with permeability recovering only slightly after the peak, remaining far below the initial value. When σ_2 is increased to 100 MPa, the ‘shear-enhanced compaction’ effect resulting from the increased compressive stress leads to significant particle friction, fracturing and compaction within the macroscopic strain zone following failure. The stress difference drives the rock’s failure mode towards a brittle transition, with a fully developed continuous shear strain zone. Permeability exhibits a rapid and substantial recovery, the post-peak permeability enhancement effect is pronounced, and the gap between the post-failure permeability and the initial value widens further. It is proposed that intermediate principal stresses control the evolution of permeability by regulating the degree of brittle failure and shear zone development in the rock, whilst high-true triaxial stresses suppress the post-peak permeability recovery capacity through compaction.

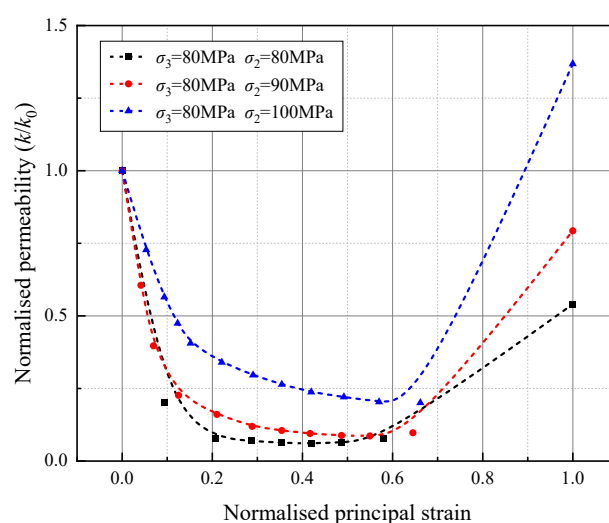


Figure 8. Normalised permeability–strain curve.

5. Limitations of the Study and Scope of the Model

The layered sandstone permeability prediction model established in this paper performs well under the laboratory test conditions adopted in this paper; however, it has certain limitations when applied to reservoirs with multiphase flow, strong anisotropy and complex stress. Affected by the inherent heterogeneity of natural sandstone, the initial permeability of different samples varies. The differences in mechanics and seepage are jointly affected by the intermediate principal stress effect and sample heterogeneity. In future research, the accuracy and engineering applicability of the model can be further improved by expanding the scope of test conditions, considering the anisotropy of bedding planes and two-phase flow problems, and verifying the model in combination with field data.

6. Conclusions

This study focuses on deep reservoir sandstones. Through true triaxial rock mechanics–seepage coupling tests, the mechanical properties and seepage evolution patterns of sandstone under high triaxial stress were systematically investigated. A staged permeability model distinguishing between elastic and damaged phases was constructed and validated, clarifying the regulatory mechanism of the intermediate principal stress on the rock mechanics–seepage coupling characteristics of sandstone. The main conclusions are as follows:

- (1) The total stress–strain process of reservoir sandstone under deep, high triaxial stress can be divided into the stages of compaction, elastic deformation, yield, and post-failure. Throughout this process, the mechanical behaviour exhibits a three-stage pattern of ‘compression–unloading and expansion–failure’, whilst the corresponding permeability exhibits a U-shaped evolution pattern characterised by ‘exponential decline–sudden increase–stabilisation’. Furthermore, the irreversible deformation of the rock’s pore structure caused by stress ensures that permeability remains at a relatively high level even after unloading, indicating that the impact of damage on sandstone permeability is irreversible.
- (2) The intermediate principal stress exerts a significant strengthening effect on the mechanical properties of sandstone. As the intermediate principal stress increases from 80 MPa to 100 MPa, both the peak strength and residual strength of the sandstone show an increasing trend; post-peak brittleness is enhanced, and ductility is reduced. Under high-intermediate principal stress conditions, the sandstone exhibits a brittle–ductile transition failure; under moderate intermediate principal stress, it exhibits ductile shear failure. By constraining lateral deformation and delaying the initiation and propagation of microcracks, the intermediate principal stress effectively increases the rock’s load-bearing limit.
- (3) The intermediate principal stress is a key factor in regulating the evolution of sandstone permeability. During the elastic stage, the initial permeability of the sandstone decreases as the intermediate principal stress increases, and the permeability decays exponentially with strain; the higher the intermediate principal stress, the faster the decay rate. In the damage stage, post-peak permeability follows the following order: specimens with low intermediate principal stress > specimens with medium intermediate principal stress > specimens with high intermediate principal stress. High intermediate principal stress suppresses the increase in permeability during the failure stage, restricts the development of crack flow pathways, and causes extensive pore closure due to true triaxial stress, making it difficult for post-peak permeability to recover to its initial value.
- (4) Based on fundamental assumptions, such as horizontal isotropy, and incorporating the Betti–Maxwell reciprocity theorem, Kachanov’s definition of damage, the Drucker–Prager criterion and Lemaitre’s principle of strain equivalence, the staged

permeability model for the elastic and damage stages of sandstone has been developed. This model is capable of characterising the quantitative relationship between permeability and strain under different stress states with high accuracy. The model's goodness of fit for the elastic stage is consistently above 0.9, whilst for the damage stage, it ranges from 0.76 to 0.85. The experimental permeability–strain data points show excellent agreement with the model's fitted curves, thereby validating the model's reliability and applicability within the stress range under investigation.

- (5) There is a clear correlation between the permeability of deep reservoir sandstone and volumetric stress. During the stress concentration phase, the compression and closure of pores and microfractures lead to a sharp decline in permeability; during the stress release phase, the reopening and expansion of microfractures cause permeability to gradually recover. At equivalent levels of volumetric stress, sandstone permeability can increase by a factor of several dozen, and the relationship between volumetric stress and permeability effectively reflects the stress concentration and release processes in deep reservoir sandstone; simultaneously, stress paths exert a significant influence on flow characteristics; the 'shear-enhanced compaction' effect triggered by increased confining pressure reinforces the post-peak permeability enhancement.

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