

Article

Dynamic Evaluation of Geological Trap Sealing for Depleted Reservoir Gas Storage Using Four-Dimensional Geomechanics

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Abstract

Underground gas storage converted from depleted oil and gas reservoirs requires reliable long-term sealing of caprocks, faults, and other geological barriers during cyclic injection and withdrawal. Conventional evaluations mainly focus on static geological parameters, whereas the effects of stress evolution during operation are often insufficiently addressed. In contrast, four-dimensional geomechanical simulations based on fluid–solid coupling can capture the dynamic evolution of geological sealing behavior under injection and withdrawal conditions. The review summarizes progress in heterogeneous geomechanical model construction, stress-field evolution under cyclic loading, dynamic sealing assessment of caprocks and faults, and determination of safe operating pressure limits. Geological sealing evaluation has evolved from a static assessment based on geological characteristics to a dynamic assessment controlled by mechanical criteria. Geostress inversion has developed from three-dimensional heterogeneous mechanical models to four-dimensional geomechanical dynamic coupling analyses that account for seepage, stress, temperature, and other factors. Safe pressure evaluation has also progressed from conventional gravity-driven storage construction to the assessment of critical pressure evolution during the safe operation stage. Existing studies indicate that heterogeneous parameter characterization, coupled flow-stress simulation, and dynamic pressure management strongly affect the reliability of sealing evaluation in reservoir-type UGS. The results further show that pressure history, stress redistribution, and creep effects should be considered together when assessing long-term storage safety. The engineering cases listed at the end of this paper verify some of the research findings. The results presented above are of great significance for the construction and safe operation of reservoir-type gas storage facilities.

Keywords: underground gas storage; geological trap; dynamic sealing evaluation; four-dimensional geomechanics; safe operating pressure



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1. Introduction

With the transition of the global energy structure and the continuous growth in natural gas demand, underground gas storage (UGS) has become key infrastructure for seasonal peak shaving and energy security. The construction scale of UGS projects has increased rapidly worldwide [1,2]. In China, UGS construction has accelerated in recent years, but development is still constrained by complex geological conditions, strong reservoir heterogeneity, and high construction and operating costs [3]. Evaluating the sealing performance of geological formations under long-term cyclic injection, production, and alternating

loading has become a focal point during the process of converting depleted oil and gas reservoirs into gas storage facilities.

The sealing capacity of UGS systems is controlled not only by the static sealing potential associated with geological attributes, but also by the dynamic sealing stability under cyclic operational pressure fluctuations [4]. Static evaluation mainly focuses on structural geometry, lithology, porosity, permeability, and fault gouge properties. Dynamic evaluation, however, requires an integrated framework involving geology, geomechanics, reservoir engineering, and fluid-flow analysis. As a result, sealing assessment has gradually developed from qualitative geological judgment to quantitative coupled evaluation based on in situ stress analysis, rock damage mechanics, and seepage mechanics.

Four-dimensional (4D) geomechanical simulation extends conventional three-dimensional (3D) spatial modeling by introducing the time dimension, thereby enabling the characterization of dynamic stress-field evolution during reservoir depletion, gas injection, and cyclic withdrawal [5,6]. By considering spatial heterogeneity and temporal variability, 4D geomechanical modeling can describe the coupled evolution of stress fields, pore pressure fields, and rock deformation under multiple cycles of injection and withdrawal. Multi-field coupled mathematical models linking fluid flow and rock deformation further enable investigation of dynamic sealing failure mechanisms, including caprock fatigue damage, microfracture propagation, permeability enhancement, and fault reactivation. These methods provide technical support for determining safe upper and lower operating pressure limits, optimizing injection-withdrawal schemes, and establishing dynamic monitoring and early-warning systems. During the conversion of depleted reservoirs into UGS, reservoir pressure experiences a complex evolution from the original formation pressure to depletion pressure and then to re-pressurization during gas injection. Such pressure cycling causes significant changes in the effective stress of the reservoir and surrounding rocks, potentially inducing rock deformation, fracture opening, or even fault slip [7].

This paper reviews recent advances in dynamic sealing evaluation for UGS converted from depleted oil and gas reservoirs. The discussion focuses on 4D geomechanical modeling methods and analyzes the static and dynamic sealing mechanisms of gas storage reservoirs, with particular attention to rock fatigue damage under cyclic pressure and fault stability variations driven by stress evolution. It also examines methods for identifying the limiting pressure capacity under dynamic injection and withdrawal conditions and proposes dynamic monitoring technologies and optimization strategies for reservoir trap sealing integrity.

2. 4D Geomechanical Modeling for UGS in Hydrocarbon Reservoirs

This section primarily reviews four-dimensional geomechanical modeling techniques for depleted oil and gas reservoirs, including heterogeneous three-dimensional geomechanical modeling, four-dimensional multi-field coupled modeling, mathematical decoupling of fluid–solid coupling, and in situ stress inversion and evolutionary simulation techniques, with a particular focus on methods and technologies for four-dimensional geomechanical simulation.

2.1. Four-Dimensional Geomechanical Modeling Workflow

4D geomechanical coupled simulation integrates both spatial and temporal parameters to investigate the dynamic evolution of in situ stress, fluid flow, and rock deformation in UGS. This modeling approach has been widely applied to gas storage reservoirs, depleted oilfield conversions, and geological CO₂ sequestration. 4D geomechanical simulations can capture the spatiotemporal variation of stresses and provide a quantitative framework for evaluating their dynamic mechanical responses. During UGS operation, disturbances in the

geostress field may not only affect long-term injection and withdrawal strategies, but also induce engineering risks, such as surrounding rock deformation, permeability alteration, and microseismicity [8]. Therefore, 4D geomechanical-coupled simulation is essential for analyzing the evolution of geological stress fields and assessing storage safety.

The main workflow for 4D geomechanical modeling includes the following steps [5,9]:

- (1) Initial geological model construction. Seismic data, well logging data, geological interpretation, and laboratory rock mechanics data are integrated to establish the spatial distributions of geomechanical parameters, including elastic modulus, Poisson's ratio, rock strength, and pore pressure.
- (2) Three-dimensional geomechanical simulation of the initial state. A 3D numerical model is established to characterize the initial stress distribution in the reservoir, caprock, faults, and surrounding formations.
- (3) Coupled flow-stress modeling. Based on historical production data, injection-withdrawal schedules, and future operation plans, a coupled fluid-flow and stress model is established to simulate pressure diffusion and stress redistribution during construction and operation.
- (4) Multi-physical field coupling. Thermal, hydraulic, mechanical, and chemical processes may be incorporated to evaluate the long-term deformation, stability, and sealing evolution of the UGS system.
- (5) Sealing capacity evaluation. The integrity of the geological trap is assessed on the basis of caprock stability, fault sealing, pressure safety margin, and wellbore integrity.

Through 4D geomechanical modeling and multi-field coupling, the sealing integrity of UGS systems can be evaluated quantitatively, which supports site selection, pressure control, and operational management [10]. The workflow of the 4D geomechanical modeling process is shown in Figure 1.

2.2. Construction of Heterogeneous Geomechanical Parameter Models

3D heterogeneous geomechanical models rely on the integration of multi-source data, including laboratory rock mechanics tests, seismic interpretation, geological modeling, and well logging information. Tests in laboratory provide key mechanical parameters, such as Young's modulus, Poisson's ratio, and compressive strength, whereas seismic and logging data are used to characterize reservoir heterogeneity in 3D space. By establishing correlations between laboratory-derived mechanical parameters and logging curves, continuous spatial distributions of mechanical properties can be constructed within the numerical model [11]. Higgins-Borchardt et al. [12] indicated that laboratory tests generally provide static mechanical parameters, whereas logging data, such as acoustic and density logs, can be used to calculate dynamic elastic modulus. Cross-validation between laboratory and logging results enables conversion between dynamic and static parameters, thereby improving the reliability of geomechanical modeling.

The construction of a heterogeneous geomechanical model also requires detailed characterization of fractures and faults within the reservoir and caprock. During gas injection in UGS, fracture and fault apertures may dynamically respond to variations in effective normal stress, permeability evolution, and sealing integrity [13]. Rouainia et al. [14] suggested that overpressure conditions may lead to leaky-seal behavior and gas leakage through the sealing layer. Therefore, the mechanical properties of heterogeneous geological materials, as well as the distribution and hydraulic-mechanical behavior of natural fractures and faults, should be accurately represented during model construction. Developing an integrated heterogeneous geomechanical parameter model for the reservoir, caprock, faults, fractures, and surrounding formations is therefore critical for reliable 4D geomechanical simulation and dynamic sealing evaluation.

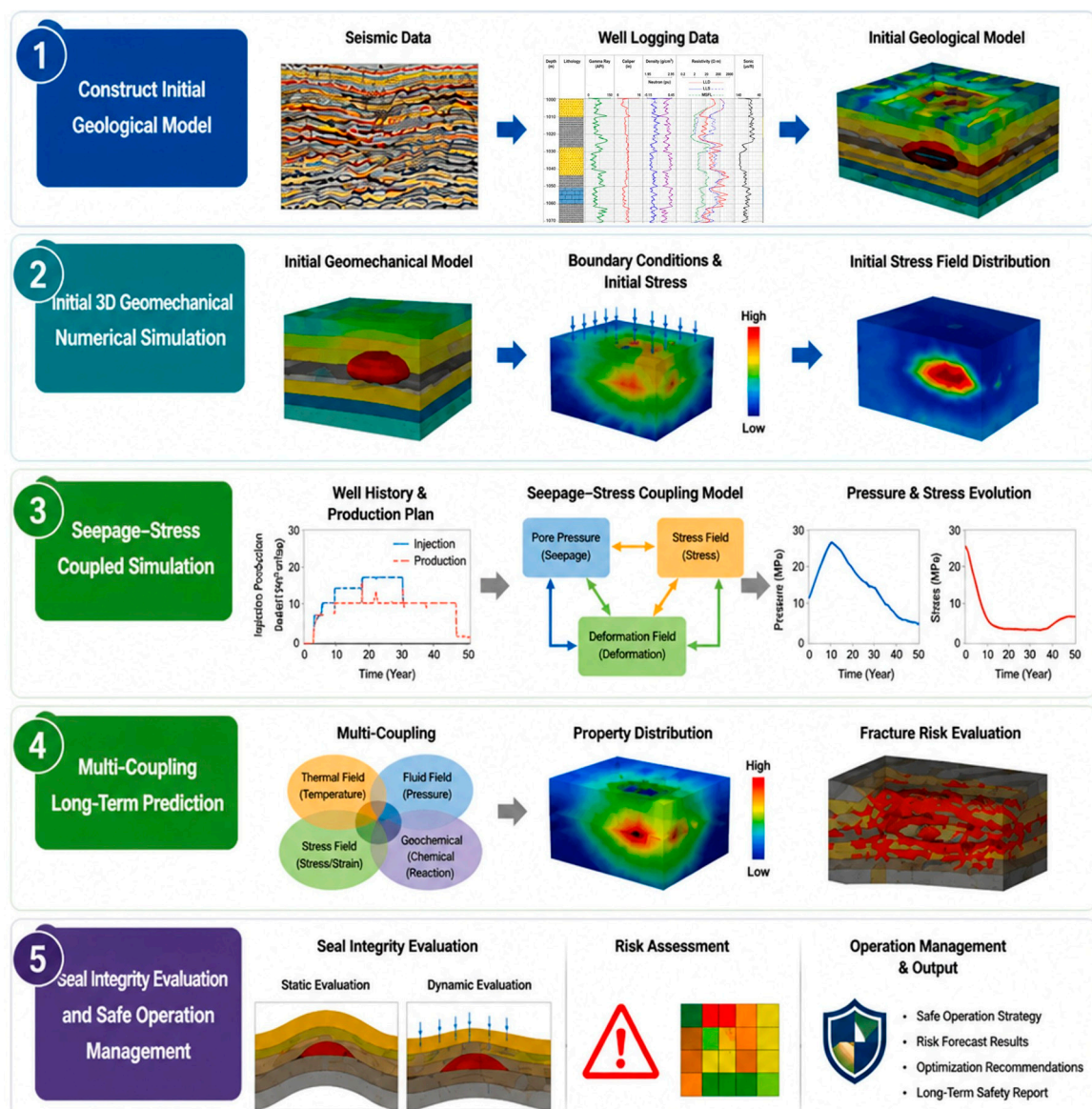


Figure 1. Workflow of 4D geomechanical modeling for underground gas storage.

2.3. Stress Evolution Under Cyclic Injection-Withdrawal Loading

During the construction and operation of UGS converted from hydrocarbon reservoirs, repeated cycles induce periodic variations in pore pressure and effective stress. 4D spatiotemporal stress simulation can be used to analyze the dynamic effects of alternating loads on the stress state of geological formations. Zhou et al. [15] indicated that rapid injection-withdrawal cycles may cause periodic fluctuations in pore pressure and effective stress, potentially leading to formation damage and natural gas leakage. Huang et al. [16] demonstrated that cyclic loading affects not only the reservoir stress state, but also the mechanical stability of surrounding geological structures. Tang et al. [17] found that alternating stresses induce dynamic changes in reservoir properties, thereby influencing UGS expansion performance. Qi et al. [18] showed that repeated gas displacement may cause particle migration and microfracture development, improving reservoir properties and enhancing storage capacity. Tang et al. [19] further revealed the synergistic regulation of permeability, pressure, and cycle number on the dynamic peak-shaving capacity of UGS. Under periodic cyclic stress, caprocks and fault rocks may experience progressive fatigue damage. Therefore, it is necessary to investigate rock fatigue behavior under different cyclic

stress amplitudes, cycle numbers, and pressure conditions through laboratory experiments, thereby providing accurate parameters for 3D stress inversion and 4D geomechanical simulation [20]. In addition, changes in stress, deformation, failure mode, creep behavior, and cyclic strength under different injection-production scenarios should be considered to prevent fatigue-induced sealing failure of geological traps.

2.4. Coupled Fluid-Stress Simulation and Numerical Solution Strategies

During gas injection and withdrawal, UGS systems exhibit significant fluid–flow–stress coupling. Therefore, constructing a multiphysics-coupled mathematical model that integrates fluid flow and rock deformation is fundamental for analyzing storage capacity variation, formation stability, and sealing integrity [21]. Current studies commonly use poroelastic coupling models based on multiphase porous media theory, incorporating the gas mass conservation equation, Darcy’s law, and mechanical equilibrium equations [22]. These models account for the dynamic evolution of gas state variables, porosity, and permeability under changing stress conditions, thereby establishing a feedback relationship between seepage and stress fields [23]. When temperature variation, fault slip, or caprock damage is considered, the model can be extended to thermo-hydro-mechanical (THM) or thermo-hydro-mechanical-damage (THMD) coupling frameworks.

From a computational perspective, coupled models are usually characterized by strong nonlinearity, multiscale parameter distributions, and complex boundary conditions. Fully coupled solutions are therefore computationally expensive and may face convergence difficulties [24]. To improve computational efficiency, several decoupling approaches have been developed, including sequential iterative decoupling, loosely coupled algorithms, and operator-splitting methods [25]. The sequential iterative method is widely used: the fluid-flow field is first solved to obtain pore pressure, which is then introduced into the mechanical equilibrium equation as a load; rock deformation and physical properties are subsequently updated iteratively until convergence is achieved [24]. The fixed-stress split method is commonly applied to Biot-type coupling problems because it reduces the number of iterations while maintaining numerical convergence [26,27].

Overall, coupled seepage–stress models for UGS are evolving from traditional dual-field coupling toward multiphysics, multiscale, and high-resolution numerical simulation. Efficient and robust decoupling algorithms are essential for extending these methods to engineering-scale applications. Although decoupling algorithms have achieved promising results, the complexity of multiphysics coupling still requires further investigation into the underlying decoupling theories and algorithms to support coupled computational analyses in complex environments.

In numerical simulations and decoupled calculations, time-dependent evolution models of damage variables, permeability, and other parameters need to be incorporated into the numerical analysis in order to more accurately calculate changes in pressure and stress. In laboratory testing, the experimental program should be adjusted in accordance with the on-site cyclic injection and production scheme, so as to obtain the variations of the damage variable (D) and permeability (k) with time (t). These results can then be converted into evolutionary curves and embedded into the numerical model for analysis and computation.

3. Static and Dynamic Evaluation of Geological Trap Sealing

Evaluation of the sealing integrity of gas storage geological bodies should be conducted from both static and dynamic perspectives. From a geological standpoint, static evaluation includes lithological distribution, spatial characteristics, and structural closure of caprocks and faults. From a mechanical standpoint, dynamic evaluation includes stress evolution during injection and withdrawal, fatigue damage in the reservoir and caprock, fault slip,

and trap integrity retention. This section reviews technologies for analyzing and evaluating stress evolution and sealing evolution under cyclic injection and withdrawal conditions.

3.1. Static and Dynamic Sealing Assessment of Caprocks and Faults

The sealing performance of UGS systems is governed by the combined influence of geological structures and the dynamic response of the pressure-stress field [3,5,7]. Based on modern geomechanics and numerical simulation techniques, UGS sealing capacity can be evaluated from three key perspectives: caprock integrity, fault sealability, and dynamic operational response [28]. Static sealing capacity primarily focuses on evaluating whether caprocks, faults, and reservoir–caprock assemblages can effectively prevent natural gas migration and dispersion [29]. Common static evaluation indicators include caprock lithology, thickness and continuity, capillary breakthrough pressure, fault sealability, and structural closure [3]. Among these indicators, caprock lithology and thickness are fundamental parameters. Mudstone, evaporite, and dense limestone commonly exhibit excellent sealing capacity because of their low permeability and fine pore-throat structure. Capillary breakthrough pressure is the key parameter determining whether the caprock can prevent upward gas migration, and it directly controls the maximum permissible gas column height and trap capacity [30]. Fault sealability is typically evaluated using shale gouge ratio (SGR), juxtaposition analysis, and fault-zone structure to determine lateral sealing effectiveness [31,32]. In general, static sealing capacity is controlled by the combined effects of capillary barriers, low-permeability segregation, and fault gouge sealing, thereby providing the geological basis for UGS site selection and construction feasibility assessment [33].

Dynamic trap sealing capacity focuses on the temporal stability of geological bodies under cyclic injection and withdrawal [28]. Pressure and stress changes may induce caprock damage, fault reactivation, and enhanced gas migration, leading to reduced sealing performance [5]. Dynamic sealing evaluation is generally based on indicators such as allowable upper and lower pressure limits, fault stability, and caprock integrity [34]. For caprocks, key concerns include minimum principal stress, tensile strain, and plastic zone development, which can be used to identify fatigue damage induced by cyclic loading [30,35]. Fault stability is commonly characterized by slip tendency and effective normal stress variation, which help determine whether fault reactivation may occur during injection-withdrawal cycles [36,37].

UGS sealing evaluation should follow the principle of “static condition determination and dynamic risk assessment.” In practical studies, static indicators, such as caprock capillary sealing capacity and fault sealability, should be integrated with dynamic indicators, such as fault reactivation risk, caprock damage evolution, and wellbore integrity. This integrated static–dynamic evaluation framework provides a basis for UGS site selection, injection-withdrawal scheme optimization, and full-lifecycle safety management [38]. Table 1 includes static indicators such as caprock lithology, thickness, shale gouge ratio, and structural closure, as well as dynamic indicators, including dynamic breakthrough pressure, operating pressure, fault slip tendency, and caprock fatigue plastic strain. Grades I–V correspond to excellent, good, moderate, poor, and very poor sealing conditions, respectively. In this context, the dynamic breakthrough pressure refers to the gas breakthrough pressure of rock under multiple cycles of loading and unloading [39]. Its evaluation range is mainly derived from the relevant code [40], which is primarily used for the assessment of petroleum- and natural-gas-related caprocks. The code defines five grades of breakthrough pressure thresholds: 15 MPa, 12 MPa, 10 MPa, and 5 MPa. Table 1 considers only the case with a safety margin of 1.

Table 1. Evaluation indicators and grading criteria for UGS sealing capacity.

Sealing Capacity Grade		Grade I	Grade II	Grade III	Grade IV	Grade V
Evaluation Results		Excellent	Good	Moderate	Poor	Very Poor
Static Evaluation Indicators	Caprock Lithology	Mudstone, Evaporite, Dense Limestone	Dense Mudstone, Multilayer Muddy Dense Caprock	Medium-Low Permeability Mudstone	Medium-High Permeability Sandy Mudstone	High Permeability Sandstone, Conglomerate
	Caprock Thickness	>300 m	250–300 m	200–250 m	150–200 m	<150 m
	Shale Gouge Ratio (SGR)	>75%	60–75%	50–60%	30–50%	<30%
	Structural Closure	Complete closure, no leakage risk	Highly effective closure, minimal leakage risk	Good closure, local leakage	Partial closure	Open structure, poor closure
Dynamic Evaluation Indicators	Dynamic Breakthrough Pressure	>15 MPa	12–15 MPa	10–12 MPa	5–10 MPa	<5 MPa
	Operating Pressure	Far below critical value, <55%	Large safety margin, 55–70%	Within safe range, 70–85%	Close to fracturing/slip pressure (85–100%)	Approaching caprock fracture/fault slip pressure (>100%)
	Fault Slip Tendency Index	No slip tendency ($ST < 0.55$)	Low slip tendency ($0.55 \leq ST < 0.7$)	Moderate slip tendency ($0.7 \leq ST < 0.85$)	High slip tendency ($0.85 \leq ST < 1.0$)	Activated fault, unstable fault ($1 \leq ST$)
	Caprock Fatigue Plastic Strain	<0.5%	0.5–1%	1–2%	2–3%	>3%

3.2. Dynamic Caprock Sealing: Fatigue Damage and Capillary Breakthrough

The caprock is the primary geological barrier preventing upward migration of natural gas. Under alternating injection and withdrawal pressures, caprock rocks may undergo fatigue damage, resulting in the formation and propagation of microfractures and seal failure. Zhang et al. [4] developed a dynamic coupled analysis method integrating geomechanics, rock damage mechanics, and seepage mechanics to evaluate caprock integrity. Wen et al. [41] proposed a semi-analytical method for assessing the dynamic sealing capacity of caprock-fault systems in UGS. Orlić et al. [42] used geomechanical numerical models to quantify production- and injection-induced stress variations and pointed out that local caprock damage and fault slip may increase permeability, thereby providing initial pathways for fluids to breach the caprock. In a study of underground hydrogen storage in depleted gas reservoirs, Zeng et al. [43] reported that alternating stress may lead to caprock fatigue damage and fracture extension. Therefore, the alternating pressure range used in laboratory fatigue tests should be designed according to actual injection and withdrawal conditions [44]. Laboratory investigations of caprock fatigue strength, damage evolution, and gas breakthrough pressure are intended to establish the relationship between fatigue strength (σ_p) and cyclic stress amplitude ($\Delta\sigma$). These parameter relationships are then incorporated into caprock mechanical simulations, with the effects of different production parameters, such as injection–production cycles, injection–production intensity, and stress amplitude, taken into account. The cumulative plastic strain from multi-cycle fatigue tests on caprocks is classified according to Table 1. Generally, values less than 1% are graded as I–II, indicating good sealing performance. Values exceeding 1% are graded as III–V, indicating moderate or poor sealing performance [3,34,44,45].

3.3. Fault Stability and Shear Slip Evaluation Driven by 4D Stress Evolution

Faults are critical potential leakage pathways in UGS traps. Under 4D stress evolution, fault stability may deteriorate, resulting in shear slip or tensile opening and consequently

sealing failure. Ma et al. [44] emphasized that evaluating fault shear slip and opening pressures during gas storage requires comprehensive consideration of in situ stress conditions, fault geometry, and fluid pressure variation. Zhuge et al. [46] evaluated the dynamic sealing capacity and site optimization of depleted-reservoir UGS by using the fault shear slip factor. Saddkhan et al. [47] pointed out that fault reactivation and fracture propagation are key factors affecting sealing integrity in hydrogen storage within depleted oil and gas reservoirs. Fu et al. [48] discussed sealing evaluation from the perspectives of fault activity, fault properties, lithology, and mechanics. Kharrat et al. [49] noted that capillary pressure and gravity play dominant roles in enhanced recovery from fractured reservoirs. Fault tensile failure occurs when the tensile stress acting on the fault exceeds its tensile strength, whereas shear failure occurs when shear stress on the fault plane exceeds the corresponding shear strength. To prevent fault opening or slip, injection and production operations should be adjusted to maintain fault stability.

At the initial stage of UGS development, faults generally remain stable, with shear stress lower than shear strength. However, during construction and operation, increasing pore pressure reduces the effective normal stress on the fault plane and consequently decreases fault shear strength. When shear stress exceeds shear strength, fault slip or failure may occur, as illustrated in Figure 2. According to the Mohr–Coulomb criterion, fault shear strength depends on effective normal stress and shear strength parameters. Therefore, the slip tendency index can be used to quantitatively characterize fault slip risk:

$$ST = \frac{\tau}{\sigma_n \mu + c}$$

where ST is the slip tendency index; τ is the shear stress (MPa); μ is the friction coefficient; c is the cohesion (MPa); and σ_n is the effective normal stress on the fault plane (MPa). The cohesion and internal friction angle of faults were determined using laboratory testing methods, as described in References [20,45].

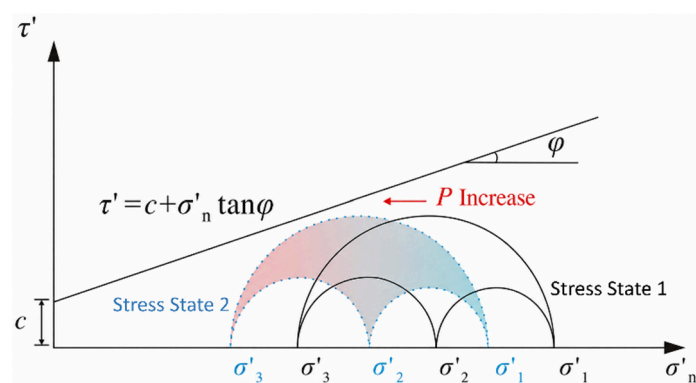


Figure 2. Mohr circle representation of the fault stress state under cyclic injection and withdrawal.

3.4. Integrated Evaluation of Trap Integrity Under Operating Pressure Constraints

The maximum injection and production pressure of UGS determines not only working gas volume and peak-shaving capacity, but also trap integrity and long-term sealing safety [3]. Quantitative evaluation of trap integrity should consider the integrated “caprock–fault–reservoir–wellbore” sealing unit by combining static geological conditions with dynamic operational responses to characterize failure risks near the upper pressure limit [44].

Regarding evaluation indicators, pressure safety margin should first be established. This includes the operational injection–production pressure range and critical thresholds such as caprock fracture pressure, capillary breakthrough pressure, and fault slip critical

pressure [45,50]. Second, caprock integrity indicators and fault stability indicators should be developed. Caprock integrity can be characterized by minimum principal stress, plastic zone development, and damage factor evolution [37,51]. Fault stability can be evaluated using slip tendency, Coulomb failure stress (CFS) variation, and SGR [52]. In addition, reservoir deformation response indicators, such as formation subsidence or uplift and reservoir stability, should be included [3]. Finally, for UGS facilities converted from depleted oil and gas fields with multiple legacy wells, wellbore integrity indicators should also be incorporated, including casing stress, casing corrosion, cementing quality, and annulus pressure anomalies [53].

In summary, trap integrity evaluation under upper injection–production pressure constraints should use pressure safety margin as the central criterion, with caprock fracturing, fault slip, enhanced fluid migration, and wellbore failure as the main risk indicators. A quantitative indicator system composed of “threshold pressure–structural stability–sealing capacity–deformation response” should be established, as shown in Figure 3. In general, the stability indicators for caprocks and faults are primarily intended to characterize the mechanical failure criterion of geological media and can be applied to different types of gas storage facilities. The arrows and dashed lines in the image are only a visual representation of this indicators and do not hold any actual significance.

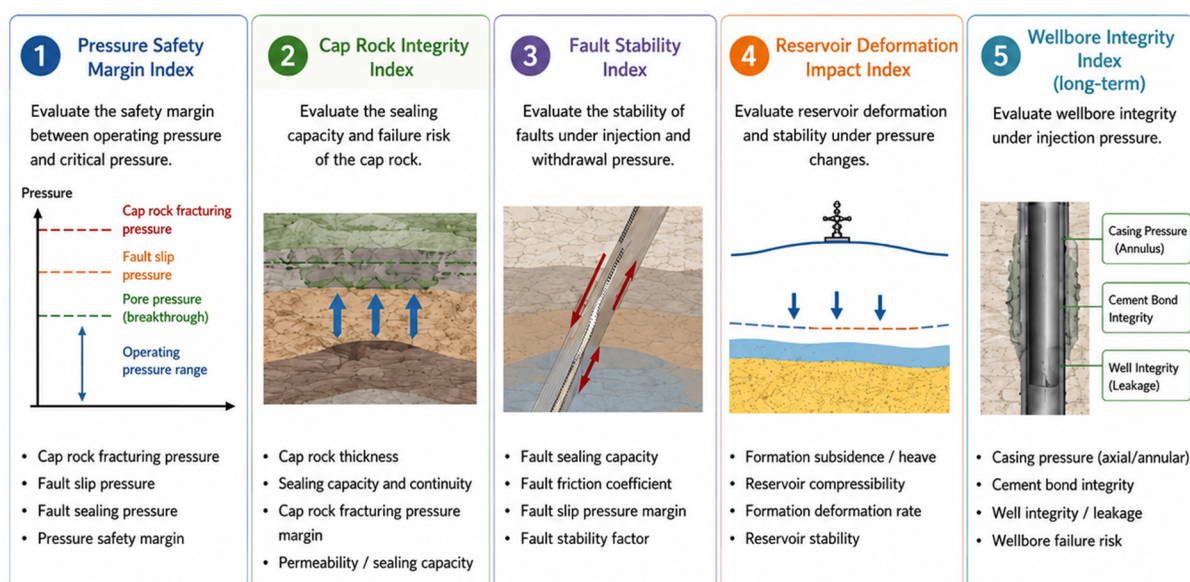


Figure 3. Integrity evaluation indicators and methods for trap structures.

4. Ultimate Pressure-Bearing Capacity and Operational Optimization

Cyclic injection and withdrawal in gas storage reservoirs induce periodically varying stresses, which may cause the sealing capacity of the geological body to reach its limit and consequently fail. Only by controlling the pressure range and injection–withdrawal frequency can the sealing integrity of the gas storage reservoir be maintained within a safe range. This section reviews the factors influencing the limiting pressure capacity under dynamic injection and withdrawal, as well as methods for determining the corresponding pressure interval.

4.1. Factors Controlling Ultimate Pressure-Bearing Capacity

The ultimate bearing capacity of a UGS geological formation is the critical safety threshold for reliable operation. During high-pressure gas injection, if reservoir pressure exceeds the minimum principal stress of the formation, hydraulic fracturing or fault reacti-

vation may occur. Downey et al. [54] emphasized that effective sealing requires caprocks with sufficient thickness and good lateral continuity. Chiaramonte et al. [55] indicated that geomechanical characterization is essential for predicting whether pressure increase may induce fault slip. Zhang et al. [4] proposed a dynamic coupling method based on geomechanics, rock damage mechanics, and seepage mechanics for determining the maximum operating pressure of UGS.

In engineering practice, logistic regression and similar statistical models are commonly used to evaluate trap leakage risk and ultimate bearing capacity. Zhu et al. [56] integrated key geological factors, such as migration pathways, reservoir quality, trap closure, and sealing effectiveness, to quantitatively assess geological risks and ultimate pressure limits. Fan et al. [57] developed a method for predicting the vertical sealing evolution of source faults to assess the sealing state of faults. Such time-dependent evolutionary analysis is crucial for determining ultimate and safe operating pressures and for evaluating UGS safety throughout its operational lifecycle.

In the above studies on ultimate pressure-bearing capacity, the focus was mainly on geological and mechanical factors, while integrated analyses of geology and mechanics were lacking, as was four-dimensional geomechanical coupling analysis. Therefore, subsequent studies need to comprehensively consider multiple factors, including geology, mechanics, and engineering, in determining the pressure-bearing limit.

4.2. Optimization of Injection–Production Schemes and Pressure Interval Regulation

Optimizing UGS operation schemes using 4D geomechanical simulation allows storage capacity utilization, peak-shaving efficiency, and trap sealing safety to be integrated into a unified evaluation framework, thereby enabling dynamic optimization of operational strategies [58]. By constructing time-dependent geomechanical models that incorporate the reservoir, caprock, faults, and wellbore systems, the evolution of pore pressure diffusion, stress redistribution, and caprock and fault stability during injection and production can be tracked [59,60]. Regarding the optimization of injection–production schemes, gas production capacity, safety, and operational efficiency are generally prioritized when determining optimal injection rates and safety pressures [51,60]. Studies have demonstrated that a management strategy involving “slow pressure ramp-up, peak capping, pressure differential regulation, and rhythmic stability” facilitates the uniform diffusion of pressure disturbances throughout the reservoir, thereby avoiding stress concentrations at fault pinch-outs, fragile caprock intervals, and areas surrounding existing wells.

For pressure interval regulation, management should shift from a single upper pressure limit to staged and regionally differentiated dynamic safety windows [45,61]. The upper pressure limit should comprehensively consider caprock tensile failure threshold, fault reactivation threshold, and wellbore sealing pressure resistance, with the most unfavorable condition used as the controlling benchmark. The lower pressure limit should ensure reservoir energy maintenance, stable production, and avoidance of rapid stress recovery [62]. Different pressure control principles should be applied during different injection–production stages. In the early injection stage, the pressure ramping rate should be controlled to prevent rapid pressure accumulation near the wellbore. In the middle and late injection stages, the duration of high pressure and the amplitude of pressure cycles should be limited to avoid cumulative caprock fatigue damage. During the production stage, pressure decline magnitude and withdrawal rate should be controlled to reduce abrupt deformation caused by stress rebound [63]. The essence of injection–production scheme optimization is to iteratively refine operational boundaries through time-dependent coupled simulation, thereby achieving precise pressure interval regulation and long-term stable UGS operation under sealing safety constraints.

5. Dynamic Monitoring and Risk Management

The identification and monitoring of sealing integrity in gas storage reservoirs require analysis from the perspective of four-dimensional geomechanical simulation, together with field monitoring, to ensure that gas within the geological trap does not leak or escape. Risk classification and early-warning technologies for leakage can help ensure stable and safe reservoir operation. This section reviews wellbore integrity monitoring and graded early-warning technologies for gas leakage risk.

5.1. Wellbore Integrity Monitoring and Real-Time Diagnosis

As one of the weakest sealing links in UGS engineering systems, wellbore integrity is directly related to the overall sealing safety of storage facilities. Casing, tubing, cement sheath, and casing–cement formation interfaces are prone to microfracturing under alternating pressure loading and stress redistribution [64]. Monitoring wellbore integrity at critical sealing intervals and conducting real-time inversion are essential technical measures for ensuring UGS operational safety [65]. In cases of trap or wellbore seal failure, the wellbore may become a preferential leakage pathway for natural gas, compromising long-term containment capacity [66,67]. Therefore, wellbore integrity assessment should extend beyond individual well components to the dynamic diagnosis of the coupled “wellbore–formation–storage complex” sealing system [68,69].

During operation, a multi-source monitoring system is commonly established, including wellhead pressure monitoring, temperature and pressure logging, annulus pressure surveillance, and casing deformation detection [67,70]. Abnormal pressure responses are effective indicators of cement sheath failure, whereas temperature anomalies can capture dynamic leakage signatures along wellbore channels [71]. Real-time inversion technologies integrate downhole monitoring data with wellbore structural parameters to develop coupled wellbore pressure–temperature–deformation models, enabling back-calculation of leakage intervals and cement sheath damage severity [71,72]. During UGS operation, wellbore integrity feedback should be incorporated into evaluations of permeability variation and casing corrosion [73]. Monitoring and real-time feedback of wellbore integrity at critical sealing intervals can improve failure identification and risk warning, while also providing key information for dynamic sealing evaluation and safety management.

5.2. Risk Grading and Early Warning Under Geological Uncertainty

Real-time monitoring and leak prediction of trap seal integrity are critical to safe operation, particularly for establishing a real-time “geology–mechanics–operation” risk early-warning system [2]. Coordinated use of conventional dynamic monitoring and real-time microseismic monitoring can form a technical framework for early warning of formation leakage risk in gas storage reservoirs, thereby guiding adjustments to injection and withdrawal operations [44]. Based on multi-cycle injection-withdrawal data, an intelligent risk identification system has been developed to enable real-time intelligent risk early warning [2]. An integrated casing–cement sheath detection system has also been developed to monitor wellbore integrity [74]. Real-time geological monitoring can use microseismic rock deformation signal identification and localization, combined with dynamic monitoring well data, to monitor and warn against risks such as caprock deformation, fault slip, and fluid leakage [75,76]. Sun et al. [77] proposed an RM-K-means-based method for quantitative risk classification of gas storage reservoirs and identified risk nodes and factors. The above scholars have made substantial contributions to real-time monitoring; however, they do not provide a detailed explanation of how integrated data analysis is conducted or how monitoring and early warning are implemented.

In terms of dynamic graded early-warning methods, grading thresholds can be set for indicators such as injection-withdrawal pressure, fault slip tendency, and caprock tensile deformation, thereby forming a safety warning system of “attention-alert-control-injection suspension” [78,79]. The first warning level reflects the upper bound of normal fluctuations and is used to identify early anomalies deviating from operating conditions. The second warning level corresponds to the onset of sensitive responses in local sealed units, indicating that reduced-rate injection-withdrawal and enhanced monitoring should be implemented; the third warning level indicates that a key sealing element of a fault, caprock, or wellbore is approaching instability and that pressure reduction or adjustment of well-group operations should be initiated immediately. And the fourth warning level corresponds to the possibility of a sudden failure in the overall sealing system, requiring suspension of high-risk wells or localized block operations. Pressure monitoring and microseismic monitoring can be used to evaluate risks such as leakage from UGS caverns, injection-withdrawal wells, and surface facilities [80]. By integrating the risk assessment methods with 4D geomechanical simulations, a comprehensive dynamic seal-risk early-warning and management system for gas storage reservoirs can be established, enabling early identification and effective control of potential leakage risks.

6. Engineering Application: L UGS

Based on engineering case studies, this section performs static sealing evaluation, cyclic loading fatigue damage analysis, four-dimensional geomechanical modeling, and dynamic sealing evaluation. These case studies verify several of the methods and technologies reviewed earlier and demonstrate their applicability.

The L UGS facility in North China was converted from a depleted oil reservoir developed by natural gas gravity drainage. The target storage interval is the third member of the Paleogene Shahejie Formation, which is characterized by interbedded sandstone, conglomerate, and mudstone. The reservoir has an average porosity of 19.1%, an average permeability of 232 mD, and an original formation pressure of 30.0 MPa. In May 2022, a pilot test of natural gas gravity drainage for enhanced oil recovery was initiated. The injection process significantly increased the reservoir pore pressure, disturbed the in situ stress field, and consequently affected the sealing integrity of the geological trap. Therefore, this case provides a representative engineering example for evaluating the sealing integrity of UGS converted from depleted oil reservoirs under cyclic injection-production conditions.

6.1. Static Sealing Evaluation of Geological Traps

The reservoir interval of the L UGS is mainly divided into oil zones 0–V. The caprocks are primarily developed at the top of oil zones 0 and IV, while six faults cut through the oil-bearing intervals and jointly control the sealing capacity of the trap, as shown in Figure 4. The sealing capacity of the caprock was evaluated using both macroscopic geological characterization and microscopic pore-structure analysis. The gray color in the figure represents mudstone, and the yellow color represents sandstone.

The caprock of oil zone IV is mainly sandy mudstone. It exhibits good lateral continuity, considerable thickness, ranging from 20 to 120 m, and wide areal distribution, indicating favorable regional sealing conditions. The caprock of oil zone 0 is dominated by mudstone, with a permeability of 0.08 mD, suggesting strong sealing performance. Microscopic testing further shows that the caprock has a pore-throat radius of 53 nm, indicating high capillary sealing capacity.

Fault sealing was evaluated based on detailed seismic interpretation and fault-rock parameter analysis. The shale gouge ratio (SGR) of the faults ranges from 60% to 70%. These indicators suggest that the fault zones contain substantial clay-rich filling materials. In

particular, fault segments F1–F6 are characterized by relatively high normal stress and well-developed clay smearing, resulting in generally favorable fault sealing capacity. Overall, the static evaluation indicates that the caprock–fault sealing system of the L UGS has a good geological basis for storage operation.

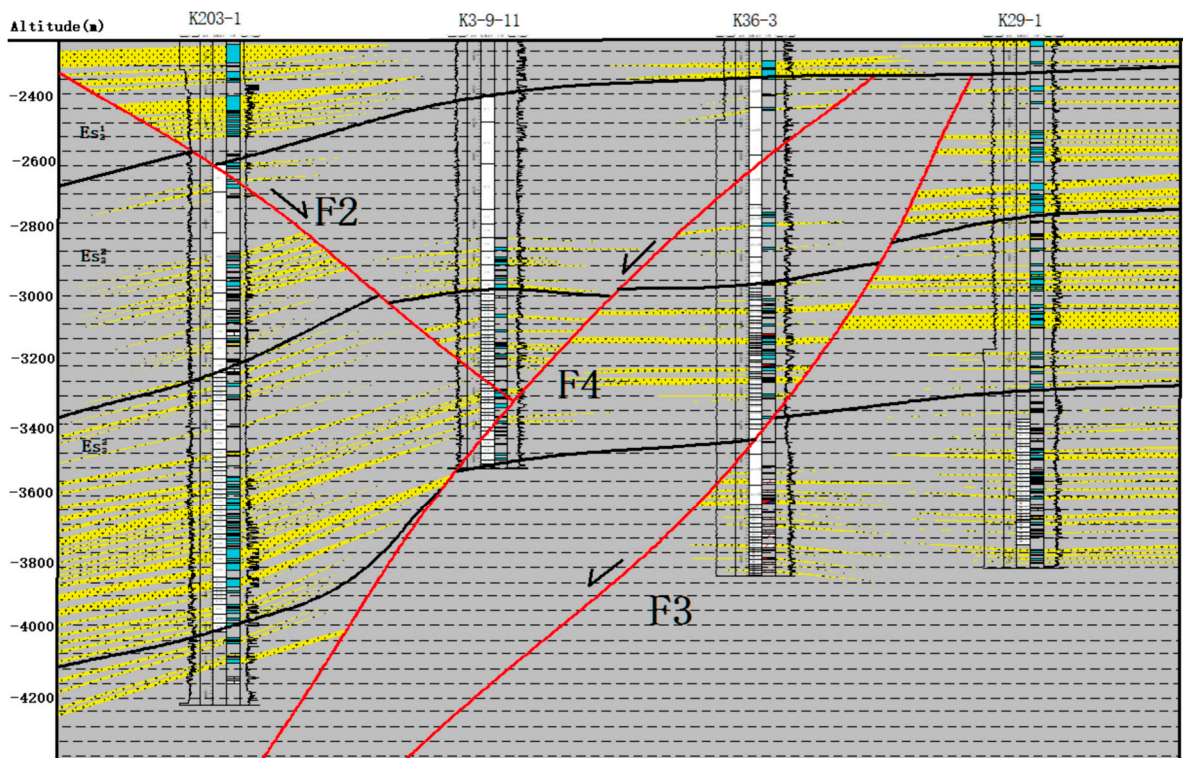


Figure 4. Geological structure and sealing elements of the L underground gas storage facility.

6.2. Fatigue Damage Analysis of Caprock Under Cyclic Pressure

During the construction and operation of underground gas storage, cyclic alternation between gas injection and production results in repeated loading and unloading of the caprock. To evaluate the fatigue resistance of the caprock, mudstone samples were collected from three wells in the storage facility. Multi-cycle fatigue tests and dynamic breakthrough pressure tests were then conducted. The cumulative plastic strain from multi-cycle fatigue tests on caprocks measured in the laboratory ranges from 0.1% to 0.9%. As can be seen from Table 1, this corresponds to a sealing grade of II, indicating good caprock-sealing performance. The dynamic breakthrough pressure ranges from 18.4 to 29.0 MPa, which is greater than 15 MPa; it corresponds to a sealing grade of I, indicating very good caprock-sealing performance. These results demonstrate that the caprock possesses high dynamic capillary sealing capacity and strong resistance to fatigue-induced degradation. Therefore, under the current operating pressure conditions, the caprock of the L underground gas storage facility is expected to maintain favorable sealing integrity during cyclic injection and production.

6.3. 4D Geomechanical Modeling and Stress Evolution

To characterize the dynamic evolution of stress and sealing integrity during storage operation, a 4D geomechanical model was established for the L UGS. The geological model was refined using well logging data and seismic interpretation results. On this basis, a 3D heterogeneous rock mechanical parameter model and an in situ stress inversion model were constructed, and a regional finite element mesh was generated for coupled fluid–solid simulation.

The model contains approximately 16 million grid cells and covers a spatial domain of $6.0 \text{ km} \times 5.6 \text{ km} \times 3.0 \text{ km}$. Reservoir simulation was first conducted to obtain the temporal evolution of pore pressure during injection and production. The simulated pore pressure field at different time steps was then transferred to the geomechanical model for fluid-stress coupling. Based on the rock constitutive equations, mechanical equilibrium equations, and boundary conditions, in situ stress inversion and dynamic stress evolution analyses were carried out for the reservoir, caprock, and fault systems, as illustrated in Figure 5.

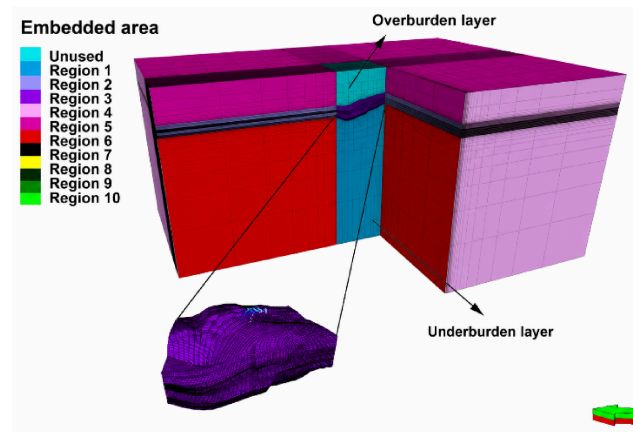


Figure 5. Schematic diagram of 4D geomechanical modeling.

The coupled simulation results reveal the dynamic response of the geological body to cyclic injection-production operations. In particular, the stress evolution at the base of the caprock was analyzed to assess the risk of tensile failure and caprock breakthrough. Figure 6 shows the variation in minimum principal stress at the base of the caprock during the gas injection stage. The minimum principal stress increases from 498 to 523 bar with increasing injection-production time, indicating a gradual increase in compressive stress during storage operation. This stress evolution is favorable for maintaining caprock stability and reducing the likelihood of tensile failure.

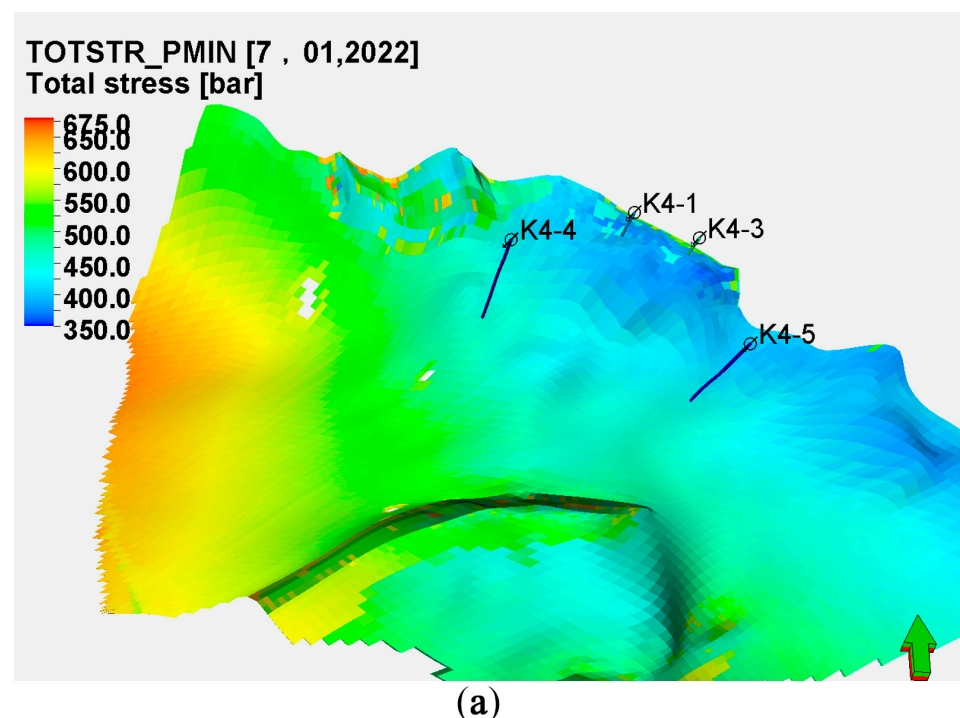


Figure 6. Cont.

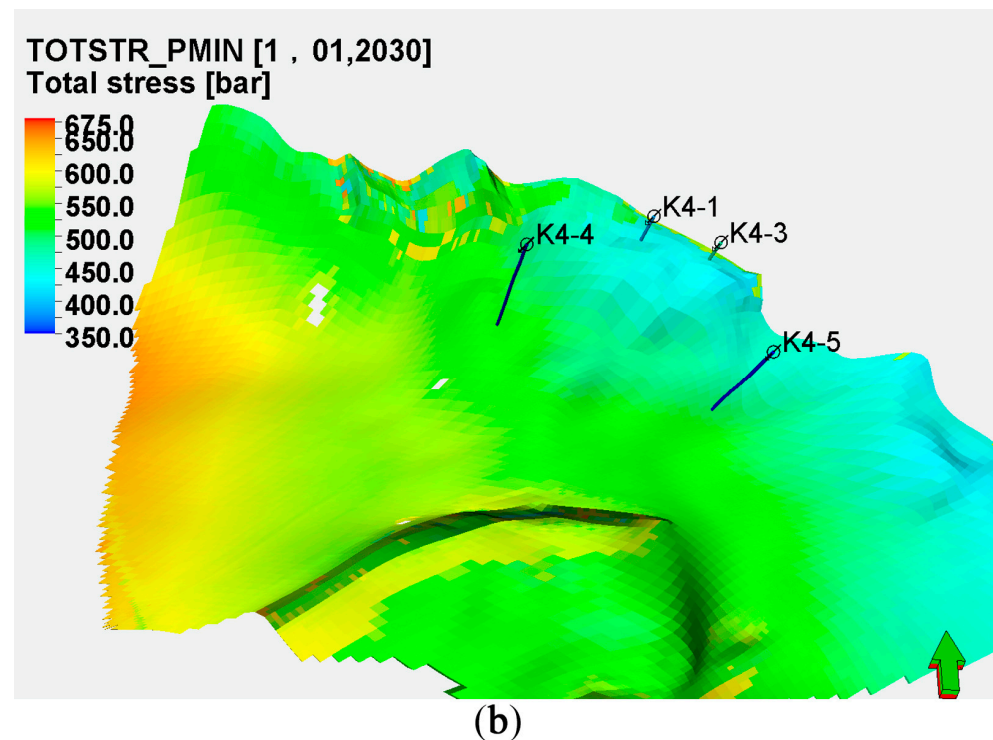


Figure 6. Variation of minimum principal stress in the base caprock. (a) Early stage of gas injection in 2022. (b) Middle stage of gas injection in 2030.

6.4. Dynamic Sealing Integrity Evaluation

The regional geostress field is dominated by vertical principal stress, with strong horizontal tectonic compression, and overall low tendencies toward failure. As injection-production time progresses, the overall variation in geostress within the geological body is limited; however, reservoir pore pressure gradually increases, leading to corresponding reductions in effective stress. This results in a declining trend of sealing integrity, though it remains within the safe operational range. Fault slip tendency indices range from 0.40 to 0.65, indicating a safe sealing status. Figure 7 shows the spatial distribution of the slip tendency index for fault F1 in 2020 and 2025. The dynamic sealing capacity of the fault system is considered acceptable during the evaluated operation period. Among all evaluated locations, the top of the fault exhibited the maximum slip tendency index, suggesting that this area is in the most unfavorable state and requires real-time monitoring of potential slip. It is recommended to strengthen stability monitoring in this zone.

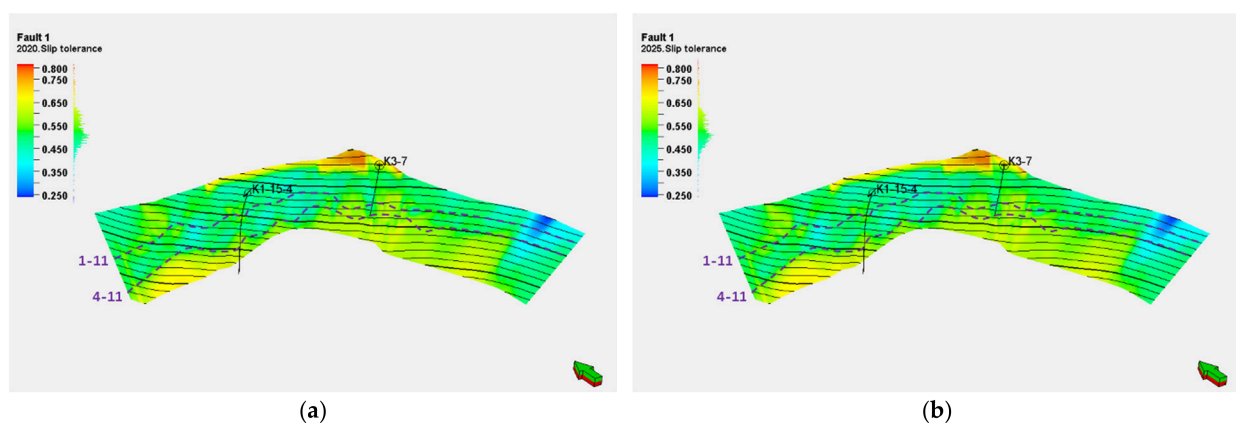


Figure 7. Distribution map of slip tendency index for Fault F1. (a) ST in 2020. (b) ST in 2025.

7. Conclusions

Dynamic evaluation of trap sealing integrity for underground gas storage converted from depleted oil and gas reservoirs is a complex multidisciplinary engineering problem involving reservoir engineering, structural geology, rock mechanics, fluid–solid coupling, and risk monitoring. Based on 4D geomechanics, this study systematically reviews recent research progress in dynamic trap sealing evaluation, including 4D geomechanical modeling, caprock and fault sealing mechanisms, ultimate bearing capacity assessment, and dynamic monitoring strategies for geological traps.

- (1) The construction of a high-precision four-dimensional heterogeneous geomechanical model is the basis for dynamic evaluation. Considering the spatiotemporal evolution of cyclic stress under multiphysics coupling, as well as the evolution of the physical and mechanical properties of the geological body, is critical to ensuring dynamic sealing integrity.
- (2) Cyclic pressure variations can induce fatigue damage in caprock rocks, and dynamic stress evolution may cause fault slippage. Assessing the dynamic sealing integrity of a geological body under stress changes is crucial for constraining the upper and lower pressure limits and ensuring the safe operation of gas storage reservoirs.
- (3) Injection and withdrawal scheme optimization based on four-dimensional geomechanical simulation, real-time in situ stress inversion, dynamic sealing evaluation, and leakage risk management technologies can effectively improve the operational efficiency and safety management of gas storage reservoirs.
- (4) The findings reviewed in this study are mainly applicable to gas storage reservoirs reconstructed from sandstone, carbonate, and other reservoir types. Further research should be conducted in conjunction with the reconstruction characteristics and reservoir-building features of different lithologies, so as to ensure the safe sealing and efficient operation of various types of gas storage reservoirs.
- (5) Reservoir-type gas storage facilities need to strengthen the decoupled computation of multiphysics-coupled models to improve the computational efficiency and accuracy of numerical simulations. They also need to enhance the integrated analysis of multi-source data and develop intelligent risk early-warning and decision-support systems.

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