Mechanical Stability Analysis of Fault Activation Under Compressed-Air Energy Storage

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Abstract

To address the unclear mechanical stability patterns of concealed faults in the surrounding rock of gas storage reservoirs, numerical simulation was adopted, with an underground gas storage reservoir in an abandoned coal mine containing a faulted surrounding rock mass as the research object. A thermo-hydro-mechanical coupling model for compressed air energy storage was established, and the influence of faults on gas storage reservoir stability, as well as the effects of sensitivity parameters such as gas injection rate, cycle period, fault dip angle, and burial depth on fault stability, were analyzed. The results show that faults increase the maximum radial displacement on the side of the cavern but reduce the maximum radial displacement at the roof, thereby helping to resist ground-surface uplift failure. Among the fault sensitivity parameters, burial depth has the greatest influence, followed by fault dip angle, while gas injection rate has the smallest influence. With increasing gas injection rate and cycle period, the fault slip tendency increases linearly, and the fault safety factor FOS decreases linearly. With increasing burial depth, the fault slip tendency rises exponentially, while the fault safety factor FOS (factor of safety) decreases exponentially. When the fault dip angle is 70°, the fault stability is the highest, reaching the extremum of the parabolic curve. The conclusions provide a scientific reference for the service life and safety of gas storage reservoirs.

Full Text

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Abstract: In view of the unclear mechanical stability laws of concealed faults in the surrounding rock of gas-storage reservoirs, numerical simulation was adopted. Taking an underground gas-storage reservoir in an abandoned coal mine with faulted surrounding rock as the research object, a thermal-fluid-solid coupled model of compressed-air energy storage was established. The influence of faults on the stability of the gas-storage reservoir was analyzed, as were the effects of sensitive parameters—including gas injection rate, cycle period, fault dip angle, and burial depth—on fault stability. The results show that the fault increases the maximum radial displacement on the side of the cavern but reduces the maximum radial displacement at the top, thereby helping to resist surface-uplift failure. Among the fault sensitivity parameters, burial depth has the greatest influence, followed by fault dip angle, while gas injection rate has the smallest influence. As the gas injection rate and cycle period increase, the sliding tendency of the fault increases linearly, and the fault safety factor FOS decreases linearly. As burial depth increases, the sliding tendency of the fault rises exponentially, and the fault safety factor FOS (factor of safety) decreases exponentially. When the fault dip angle is 70°, fault stability is the greatest, reaching the extremum point of the parabolic curve. The conclusions provide a scientific reference for the service life and safety of gas-storage reservoirs.

Keywords: underground compressed-air energy storage; abandoned coal mine; underground cavern; fault; stability; numerical simulation

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Mechanical Stability Analysis of Fault Activation Under the Action of Compressed Gas Energy Storage

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Abstract: In view of the fact that the mechanical stability law of buried faults in the surrounding rock of gas storage is not clear, the numerical simulation method is used to establish the thermal-fluid-solid coupling model of compressed gas energy storage by taking the abandoned coal mine underground gas storage with fault surrounding rock as the research object. The influence of faults on the stability of gas storage and the influence of sensitive parameters such as gas injection rate, cycle period, fault dip angle and buried depth of gas storage on the stability of faults are analyzed. The results show that the fault increases the maximum radial displacement of the side of the cavern, but decreases the maximum radial displacement of the top, which has the effect of resisting the surface uplift damage. Among the fault sensitivity parameters, the buried depth has the greatest influence, the fault dip angle is second, and the gas injection rate is the

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smallest. As the gas injection rate and cycle period increase, the sliding tendency of the fault increases linearly, while the fault safety factor FOS decreases linearly. As burial depth increases, the sliding tendency of the fault increases exponentially, while the fault safety factor FOS decreases exponentially. When the fault dip angle is 70°, the fault stability is the greatest, reaching the extremum of the parabola. The conclusions obtained provide a scientific reference for the service life and safety of gas storage.

Key words: underground compressed air energy storage; abandoned coal mine; lined cavern; fault; stability; numerical simulation

In recent years, supported by national strategic priorities, new energy has developed rapidly[1]. However, its inherent intermittency and fluctuation are the main obstacles to grid integration. Compressed air energy storage (CAES) is a large-scale energy storage technology for solving this problem[2–3]. According to research by the Chinese Academy of Engineering, a large number of coal mines in China have been closed[4]. Using abandoned coal mines as underground caverns for CAES and reusing underground space has long been a research hotspot in recent years[5]. The underground space of abandoned coal mines is structurally complex, and fault systems are widely distributed in the crust. Under the disturbance caused by the periodic variation of gas-storage reservoirs, faults may become activated, thereby triggering a series of safety problems. Therefore, research on fault stability is a key technology for the construction of underground gas-storage reservoirs.

In recent years, experts and scholars have carried out extensive research on the mechanical stability of underground caverns and faults. Jiang Zhongming et al.[6–8] performed a series of theoretical derivations, obtained formulas for calculating the energy-storage efficiency of underground gas-storage reservoirs and a thermodynamic model of compressed air considering the influence of air humidity, and conducted numerical simulations of the Pingjiang compressed-air energy-storage test reservoir to analyze its mechanical characteristics under cyclic temperature and pressure. Xia Caichu et al.[9] used Abaqus to analyze underground gas-storage structures with different burial depths and different cross-sectional shapes, and studied the plastic zones and circumferential strains of the surrounding rock of hard-rock gas-storage caverns under two working conditions: excavation and gas charging. Jiang Zhongming et al.[10] developed a lining-crack analysis program based on the FLAC 3D platform, and investigated the effects of lining reinforcement mode, reinforcement ratio, concrete cover thickness, surrounding-rock category, and cyclic thermo-pressure loading on the evolution characteristics of lining cracking. Xu Yingjun et al.[11], based on the upper-bound theorem of limit analysis, derived expressions for the cavern heave-failure function $f(x)$ and the ultimate internal pressure p_u, as well as design criteria against heave failure, and performed sensitivity analysis on the parameters affecting the cavern heave-failure function $f(x)$ and ultimate internal pressure p_u. ZHOU et al.[12] constructed a thermo-mechanical damage model through COMSOL numerical simulation and analyzed the effects of heterogeneity and weak planes on the long-term stability of lined rock caverns for underground compressed-air energy storage. POLAŃSKI et al.[13] established a model based on the parameters of the Huntorf power plant, and, according to different stress criteria and cavern stresses in the rock mass at different time intervals, determined the effects of temperature and salt creep rate on the stability of storage caverns. HAN et al.[14] conducted confining-pressure unloading tests on salt rock at six unloading rates, establishing the relationships among unloading rate, rock failure, and gas withdrawal rate. HUBBERT et al.[15] considered the role of fluid pressure in fault stability, proposed the hydraulic fracturing mechanism, and argued that when the fluid pressure is sufficiently high, activation of potential faults is very likely. Zhang Jianyong et al.[16], based on extensive literature and cases, studied the mechanisms, influencing factors, risk-assessment methods, and countermeasures associated with fault activation and induced low-magnitude earthquakes caused by high-pressure fluid injection. Jiao Yu et al.[17] analyzed, through laboratory tests, the relationships between the frictional strength and frictional sliding stability of fault zones and the saturation of minerals in the fluid. BAISCH et al.[18] used a numerical fault model considering the dilatancy effect to simulate the overpressure phenomenon of fluid injection and the process of induced earthquakes. WU et al.[19] summarized the key characteristics of fault activation induced by fluid injection and introduced strategies for mitigating fault instability in new-energy projects such as natural gas. CHENG et al.[20] analyzed the stress state, acoustic emission and microseismic activity during the activation process of concealed brittle faults, and the relationships among their parameters, concluding that MS (i.e., microseismic) monitoring is feasible. JIANG et al.[21] used the discrete-element software UDEC to analyze the evolution law of fault activation and instability under mining action. Xu Zengguang et al.[22] analyzed 11 key factors, including fault-zone width and fault properties, as evaluation indices, and established a risk-evaluation system for water and mud inrush in shallow-buried river-crossing tunnels in karst areas. Chen Fei et al.[23] established a fluid–solid coupling model using the finite-element software ADINA and obtained the optimal intersection-angle ranges between pipelines and different types of faults.

In summary, scholars in China and abroad have conducted extensive analyses of the mechanical stability of underground caverns and faults. Existing studies have mainly focused on the stability of underground caverns under cyclic injection and production, and on the stability of faults subjected to fluid injection or mechanical disturbance; few have considered the stability of faults in the surrounding rock under the influence of hard-rock gas-storage caverns. For this research objective, theoretical derivation cannot comprehensively account for the influence of all factors; field tests have long time cycles, require large investments, and make data difficult to obtain; and laboratory tests cannot fully simulate engineering conditions. Numerical simulation is a better choice for large-scale models, but current studies are mostly based on fluid-solid coupling. Accordingly, taking abandoned coal-mine roadways as the research background, this study establishes a thermo-hydro-mechanical model of compressed-air energy storage, analyzes the effects of excavation damage and faults on the stability of underground caverns, and also conducts sensitivity analysis of fault stability to determine the gas-storage reservoir parameters and fault

characteristics affect it, thereby providing a scientific reference for the site selection and design of underground gas-storage caverns.

1 Establishment of the Numerical Model

The construction of gas-storage caverns can avoid large faults, but concealed faults are still unavoidable. In this study, the sealing of the underground lined cavern adopts a rubber sealing layer. The load acts entirely on the surrounding rock, while the sealing layer only plays a sealing role. An ideal-gas thermodynamic model of the cavern including air leakage and heat exchange is established. Considering the damage caused by the excavation and operation of abandoned coal mines, the gas-liquid two-phase flow in the surrounding rock is simplified as single-phase groundwater flow with a source term, and heat transfer in the surrounding rock is treated as non-isothermal heat transfer. Thus, a coupled thermal-hydraulic-mechanical damage multiphysics model for surrounding rock with excavation damage and faults is established.

1.1 Modified Thermodynamic Model

During the entire cycle of the compressed-air energy-storage cavern, temperature and density are taken as the state variables of the gas. From conservation of mass and conservation of energy of the air in the cavern, the following are obtained

:

$$V\frac{d\rho}{dt} = (F_i + F_e)\dot{m}_{ie} - \dot{m}_l \tag{1}$$

$$V\rho c_{v0}\frac{dT_d}{dt} = F_i\dot{m}_{ie}\left(h_i - h + Z_0R_dT_d - \rho\left.\frac{\partial u}{\partial\rho}\right|_{T_d}\right) + (F_e\dot{m}_{ie} - \dot{m}_l)\left(Z_0R_dT_d - \rho\left.\frac{\partial u}{\partial\rho}\right|_{T_d}\right) + \dot{Q} \tag{2}$$

$$P_d = Z\rho R_d T_d \tag{3}$$

$$h_i - h \approx c_{p0}(T_i - T_d), \quad \left.\frac{\partial u}{\partial \rho}\right|_{T_d} T_d \approx \rho \frac{R_d T_0^2 Z_{T0}}{\rho_0} \tag{4}$$

where ρ is the air density in the cavern (kg/m^3); V is the volume of the compressed-air energy-storage cavern (m^3); u and h are the specific internal energy (J/kg) and enthalpy (J/kg), respectively; $\dot{Q}$ is the heat-transfer rate at the inner surface of the surrounding rock (W); $\dot{m}_l$ is the air leakage rate from the cavern (kg/s); and the subscripts i and e denote the gas states at the cavern inlet and outlet, respectively. $(F_i + F_e)$ is the instantaneous mass-flow rate of air in the cavern (kg/s), where $\dot{m}_{ie}$ is the mass-flow rate (kg/s). F_i and F_e are dimensionless periodic functions within the periodic time t_p, as shown in Fig. 1. F_i is 1 only during the air-charging time and is 0 during the other processes; F_e is t_{CD} only during the air-release time and is 0 during the other processes. CD denotes the ratio of the mass-flow rate during air release to that during air charging. F_i and F_e respectively represent the mass-flow rates during the charging and discharging periods. The time intervals are as follows: t_1 is the charging time, $t_2 - t_1$ is the first storage time, $t_3 - t_2$ is the discharging time, and $t_p - t_3$ is the second storage time. P_d is the cavern pressure (Pa); T_d is the air temperature in the cavern (K); T_i is the temperature of the air entering the cavern (K); R_d is the gas constant $(\mathrm{J \cdot kg^{-1} \cdot K^{-1}})$; c_v and c_p are the specific heat capacities of air at constant volume and constant pressure, respectively $(\mathrm{J \cdot kg^{-1} \cdot K^{-1}})$; and c_{v0}, c_{p0}, Z_0, and Z_{T0} are respectively the calculated values of c_v, c_p, Z, and $\partial Z/\partial T$ in the initial state (T_0, ρ_0). For the ideal gas in the cavern, $Z = 1$ and $Z_{T0} = 0$.

The total heat-transfer rate generated by convective heat exchange between compressed air and the surrounding rock is

$$\dot{Q} = \frac{2h_{cV}}{r_0}\left[T_1(r_0, t) - T_d\right] \tag{5}$$

where h_c is the convective heat-transfer coefficient $(\mathrm{W \cdot m^{-2} \cdot K^{-1}})$; r_0 is the radius of the cavern (m); and $T_1(r_0, t)$ is the temperature of the surrounding-rock surface (K).

Fig. 1 The change of $F_i + F_e$ in a cycle of compressed-air energy storage.

For the content of this study, the sealing layer of the underground lined cavern of the gas-storage reservoir is a polymer-material sealing layer, such as rubber. The high-pressure air in the cavern enters the surrounding rock through the polymer sealing layer. To simulate the seepage field in the surrounding rock more accurately, this study considers the influence of leakage. The initial pressure of the surrounding rock is standard atmospheric pressure; as gas leaks, the pore pressure of the surrounding rock forms a stepped pressure gradient. With certain simplifications, the gas–liquid two-phase flow in the surrounding rock is simplified as single-phase groundwater flow with a source term. During leakage from the underground cavern, the rubber sealing layer plays the primary role, and the leakage term of the cavern is solved using the gas-permeation equation for polymer materials. To simplify the calculation, this study adopts the steady-state gas-permeation equation for polymer materials, giving

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$$\dot{m}_l(t) = \rho_s A_d \lambda \left(\frac{P_d - P_{\text{out}}}{h_m} \right) \tag{6}$$

where ρ_s is the air density at 0°C and standard atmospheric pressure (kg/m^3), with $\rho_s = 1.29$ kg/m^3; A_d is the cavern surface area (m^2); λ is the permeability coefficient of the polymer material; P_{out} is the groundwater pressure outside the polymer sealing layer, $P_{\text{out}} = \rho_l g h_p$, where ρ_l is the groundwater density, g is the gravitational acceleration, and h_p is the distance between the cavern and the ground surface.

1.2 Governing Equations for the Surrounding Rock

$$G u_{i,kk} + \frac{G}{1-2\nu} u_{k,ki} - K' \alpha_T T_{,i} - \alpha P_{,i} + f_i = 0 \tag{7}$$

In the formula, G is the shear modulus of the surrounding-rock matrix; u_i is the displacement component; ν is the Poisson' s ratio of the surrounding rock; K' is the bulk modulus of the surrounding rock; α_T is the coefficient of volumetric expansion under constant pore pressure and stress; $T_{,i}$ is the component of the surrounding-rock temperature; α is the Biot coefficient; $P_{,i}$ is the pore pressure; f_i is the body force; and the effective stress is defined as $\sigma'_{i,k} = \sigma_{i,k} - \alpha P \delta_{i,k}$. The governing equation for groundwater flow in the surrounding rock is

$$\left\{ \frac{1-\varphi_0}{1+\varepsilon_v} \alpha \rho_l + \frac{\rho_l C_{lp}}{\left[1 - C_{lp}(P-P_0)\right]^2} \varphi \right\} \frac{\partial P}{\partial t} + \left\{ \frac{n - 2eT + 3wT^2}{1 - C_{lp}(P-P_0)} \varphi - \frac{1-\varphi_0}{1+\varepsilon_v} \alpha_T \rho_l \right\} \frac{\partial T}{\partial t}$$
$$+ \frac{1-\varphi_0}{1+\varepsilon_v} \rho_l \frac{\partial \varepsilon_v}{\partial t} - \left\{ \frac{\rho_l k}{\mu_l} \frac{\partial^2 P}{\partial x^2} + 2 \frac{\rho_l k}{\mu_l} \frac{\partial^2 P}{\partial xy} + \frac{\rho_l k}{\mu_l} \frac{\partial^2 P}{\partial y^2} + \frac{\partial}{\partial x} \left(\frac{\rho_l^2 k}{\mu_l} g \right) + \frac{\partial}{\partial y} \left(\frac{\rho_l^2 k}{\mu_l} g \right) \right\} = Q_s \tag{8}$$

where φ_0 is the initial porosity of the surrounding rock; ε_v is the volumetric strain; $\rho_l = \dfrac{\rho_{lT}}{1 - C_{lp}(P-P_0)}$ is the groundwater density; C_{lp} is the compressibility of water, taken in this study as 0.465 GPa^{-1}; P_0 is the reference water pressure, taken in this study as 0; φ is the porosity of the surrounding rock; $n = 0.020229$, $e = 0.00602137$, $w = 0.0000163$; k is the permeability of the surrounding rock; $\mu_l = 0.6612\,(T - 229)^{-1.562}$ is the dynamic viscosity of groundwater; and Q_s is the source term. The dynamic porosity is

$$\varphi = 1 - \frac{(1-\varphi_0)}{1+\varepsilon_v}\left[1 - \frac{1}{K'}[\alpha(P-P_0)] + \alpha_T(T-T_0) - (\varepsilon_v - \varepsilon_{v0})\right] \tag{9}$$

The dynamic permeability is

$$k = k_0\left\{\frac{1}{\varphi_0} - \frac{1-\varphi_0}{(1+\varepsilon_v)\varphi_0}\left[1 - \frac{1}{K'}[\alpha(P-P_0)] + \alpha_T(T-T_0) - (\varepsilon_v - \varepsilon_{v0})\right]\right\}^3 \tag{10}$$

Considering convective heat transfer and heat conduction between the surrounding rock and the gas in the cavern, according to energy conservation, the governing equation for the temperature field in the surrounding rock is

$$(\rho C)_M \frac{\partial T}{\partial t} - TK_l\alpha_l\nabla\cdot\left(\frac{k}{\mu_l}\nabla P\right) + TK_l'\alpha_T\frac{\partial \varepsilon_v}{\partial t} = \beta_M\nabla^2 T + \rho_l C_l\frac{k}{\mu_l}\nabla P\nabla T + \dot{Q} \tag{11}$$

where $(\rho C)_M$ is the specific heat capacity of the surrounding-rock matrix; $K_l = 0.465\ \mathrm{GPa}^{-1}$ is the bulk modulus of groundwater; α_l is the thermal expansion coefficient of groundwater at normal temperature and pressure, $\alpha_l = 3.4 \times 10^{-4}$ (1/K); β_M is the thermal conductivity of the surrounding rock; and C_l is the constant-volume specific heat constant of groundwater.

1.3 Multi-field coupled numerical model

To fully simulate realistic operating conditions, the surrounding rock of the underground cavern is divided into a damaged zone, a disturbed zone, and an intact zone. The distribution of the excavation-damaged region, geometric dimensions, and boundary conditions are shown in Fig. 2. The abandoned-coal-mine underground gas-storage cavern has a burial depth of 100 m, a roadway radius of 2.5 m, and a cavern volume of 10^5 m^3. The geothermal temperature is 10 °C, and the initial temperature is distributed according to a vertical gradient of 0.03 °C/m. The initial pressure is one atmosphere, and the inlet boundary is the gas leakage velocity from the cavern into the surrounding rock, $m_l(t)$. The operating schedule is a daily cyclic power-generation mode consisting of 8 h of charging, 4 h of storage, 4 h of discharging, 8 h of storage, and 4 h of energy storage. To further simulate the influence of permeability on the fracture zone for faults in the surrounding rock, the fault is divided into a fault core and a damage zone. The dip angle of the fault is 60°, and its horizontal distance from the center of the underground cavern is 46 m. The model contains 3,542 elements, 543 boundary elements, and 25 vertex elements, and the minimum element quality is 0.35006.

Fig. 2 Lined cavern size, model grid and boundary conditions of compressed air energy storage

Table 1 Basic parameters used in numerical simulation calculation

Calculation parameter	Value
Cavern length H /m	5.093×10^3
Injected-air temperature T_i /K	294.65
Air mass flow rate m_{ie} /$(\mathrm{kg} \cdot \mathrm{s}^{-1})$	100
Initial cavern pressure P_{d0} /Pa	5×10^6
Initial cavern temperature T_{d0} /K	286.15

Table 1 (continued)

Computational parameter	Value
Heat-exchange coefficient h_c / $(\mathrm{W} \cdot \mathrm{m}^{-2} \cdot \mathrm{k}^{-1})$	30
Initial rock permeability k_0/m^2	1×10^{-17}
Initial rock porosity φ	0.01
Young' s modulus of rock E/GPa	35
Young' s modulus of rock grains E_s/GPa	105
Poisson' s ratio of rock ν	0.3
Rock density ρ_s / $(\mathrm{kg} \cdot \mathrm{m}^{-3})$	2700
Thermal conductivity coefficient of rock β_r / $(\mathrm{J} \cdot \mathrm{m}^{-1} \cdot \mathrm{s}^{-1} \cdot \mathrm{K}^{-1})$	3
Thermal expansion coefficient of rock α_T / (K^{-1})	1×10^{-5}
Specific heat capacity of rock C_r / $(\mathrm{J} \cdot \mathrm{kg}^{-1} \cdot \mathrm{K}^{-1})$	0.9×10^3
Specific heat capacity of groundwater C_l / $(\mathrm{J} \cdot \mathrm{kg}^{-1} \cdot \mathrm{K}^{-1})$	4.2×10^3
Permeability coefficient of the sealing layer λ	2.43×10^{-17}
Initial permeability of rock in the damaged zone k_{10}/m^2	1×10^{-12}
Initial porosity of rock in the damaged zone φ_1	0.464
Young' s modulus of rock in the damaged zone E_1/GPa	18.2

Computational parameter	Value
Initial permeability of rock in the disturbed zone k_{20}/m^2	1×10^{-16}
Initial porosity of rock in the disturbed zone φ_2	0.02
Young' s modulus of rock in the disturbed zone E_2/GPa	31.5
Initial permeability of rock in the damage band k_{30}/m^2	1×10^{-13}
Initial porosity of rock in the damage band φ_3	0.32
Young' s modulus of rock in the damage band E_3/GPa	17.5
Poisson' s ratio of rock in the damage band ν_1	0.32
Initial permeability of fault-core rock k_{40}/m^2	1×10^{-17}
Initial porosity of fault-core rock φ_4	0.25
Young' s modulus of fault-core rock E_4/GPa	28
Poisson' s ratio of fault-core rock ν_2	0.25
Time point t_1/h	8
Time point t_2/h	12
Time point t_3/h	16
Time point t_p/h	24

2 Model Validation

2.1 Model Reliability Validation

The numerical simulation model for the abandoned-coal-mine underground gas storage reservoir in this study was validated by comparison with the numerical simulation results of the compressed-air energy-storage test project of KIM et al.

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The comparison of the variation trends of gas temperature and pressure in the underground gas storage reservoir is shown in Fig. 3 and Fig. 4. By comparing the numerical simulation model of this study with the model of KIM, it is found that the variation trends of the two remain consistent, the magnitudes that can be reached are basically the same, and the fitting degree of the two curves is relatively high.

Fig. 6 Comparison of simulation results under different grid schemes

Figure 1: Fig. 6 Comparison of simulation results under different grid schemes

Fig. 3 Changes in pressure for model reliability verification

Fig. 3 Model reliability verification pressure changes

Fig. 4 Changes in temperature for model reliability verification

Fig. 4 Model reliability verification temperature changes

Sealing performance is an important indicator for a gas storage reservoir. The simulated air leakage rate within one day for the lined cavern of compressed-air energy storage is shown in Fig. 5. Processing the data in the figure and integrating gives a leakage amount in one cycle of approximately 2 kg; the value lies within the requirement that the daily air leakage rate be less than 1%. Verification shows that this numerical model is accurate and reliable.

Fig. 5 Air leakage rate during one cycle of operation

Fig. 5 Air leakage rate in one cycle of operation

2.2 Mesh-Independence Verification

In this study, three groups of mesh schemes were established: the model contains 3,542 elements, 543 boundary elements, and 25 vertex elements, with a minimum element mass of 0.35006; the model contains 4,816 elements, 625 boundary elements, and 31 vertex elements, with a minimum element mass of 0.4499; the model contains 16,981 elements, 914 boundary elements, and 31 vertex elements, with a minimum element mass of 0.48. The results for the radial displacement of the cavern sidewall were compared. As shown in Fig. 6, under the different mesh schemes, the variation trends of the sidewall radial displacement are consistent, the difference in the maximum values is small, and the influence of the total number and size of elements on the results can be neglected.

Fig. 6 Comparison of simulation results under different grid schemes

3 Results Analysis

Many studies have been carried out on the design of CAES underground gas-storage caverns. However, under conditions where faults are present in the surrounding rock, the effects on the stability of underground gas-storage caverns and on the mechanical stability of fault activation remain unclear. This study focuses on these issues and investigates the interaction between the two, providing a basis for the safe construction of gas-storage caverns.

3.1 Stability of the Lined Cavern

Using empirical formulas based on Platts theory, the allowable displacement of the underground cavern is obtained as the criterion for stability judgment

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$$\delta_t = 12B/R_d^{3/2} \tag{12}$$

$$\delta_s = 4.5B^{3/2}/R_d^2 \tag{13}$$

In the formulas, δ_t and δ_s are respectively the allowable maximum radial displacements of the cavern roof and sidewall (m); B is the cavern span (m). $R_d = 38.54$ MPa is the uniaxial compressive strength of the surrounding rock. For the numerical model in this study, the calculated allowable maximum radial displacement is $\delta_t = 0.25$ m at the roof and $\delta_s = 0.03$ m at the sidewall. Thus, the allowable maximum radial displacement is used as the criterion for cavern stability.

The excavation-damaged zone, the fault zone, and the intact zone in the surrounding rock of the underground gas-storage cavern have different material properties. In addition, the material properties within the excavation-damaged zone and the fault zone are not identical; among them, the permeability differs relatively greatly, by several orders of magnitude. Therefore, this study divides the analysis into three working conditions: surrounding rock with excavation damage (damage hole side and damaged roof); surrounding rock without excavation damage (no damage hole side and no damaged roof); and surrounding rock with excavation damage and a fault (fault hole side and fault roof). Figure 7 compares the maximum radial displacement at the roof and sidewall of the cavern. For the surrounding rock with excavation damage and a fault, the maximum radial displacement of the sidewall is 0.43 mm and the maximum radial displacement of the roof is −0.09 mm; both maximum radial displacements are within the allowable displacement range given by the above formulas. Compared with condition 2, conditions 1 and 3 show an increase in the maximum radial displacement of the sidewall; condition 3 increases by 32.8% relative to condition 2, indicating that the fault has a greater influence on the maximum radial displacement of the sidewall. For the maximum radial displacement of the roof, condition 1 increases relative to condition 2, while conditions 3 and 2 are nearly the same, indicating that the fault has a weaker effect on the maximum radial displacement of the roof. The excavation-damaged zone increases the maximum radial displacement of the cavern roof and sidewall; the fault substantially increases the maximum radial displacement of the cavern sidewall, but weakens the maximum radial displacement of the cavern roof.

Fig. 7 Comparison of cavern displacement under different working conditions

Figure 2: Fig. 7 Comparison of cavern displacement under different working conditions

Fig. 7 Comparison of cavern displacement under different working conditions

The variation trends of the maximum radial displacement at the roof and sidewall of the CAES cavern over 30 cycles are shown in Fig. 8. As the operating cycles of the gas-storage cavern increase, the radial displacement at the roof increases, while the radial displacement at the sidewall decreases slightly. After 30 cycles of operation, under condition 1, the increase in the maximum radial displacement at the cavern roof is the largest, at 0.82 mm; under condition 3, the increase in the maximum radial displacement at the cavern roof is the smallest, at 0.43 mm. After 30 cycles of operation, the maximum radial displacement of the cavern sidewall remains relatively stable, with a displacement variation of about 0.1 mm. In addition, as the operating cycles of the gas-storage cavern continue to increase, the displacement at the cavern roof is greater than that at the sidewall. In summary, the fault has a positive influence on the stability of the underground gas-storage cavern and helps the underground cavern resist uplift failure.

(a) Variation trend of cavern displacement under Working Condition 1

(b) Variation trend of cavern displacement under Working Condition 2

(c) Variation trend of cavern displacement under Working Condition 3

Fig. 8 Comparison of displacement variation trends of the cavern under different working conditions

3.2 Evaluation Criteria for Fault Stability

At present, evaluations of fault stability are mostly established on the basis of the Mohr-Coulomb criterion without considering cohesion. There are mainly two evaluation indices for fault stability: slip tendency (T_s) [28] and factor of safety (FOS) [29]. Their definitions are respectively

$$T_s = \frac{\tau}{\sigma_n - P_f} \tag{14}$$

$$\mathrm{FOS} = \frac{(\sigma_n - P_f)\tan\varphi}{\tau} \tag{15}$$

where τ is the actual shear stress; σ_n is the actual normal stress; P_f is the pore pressure; and $\tan\varphi$ is the fault friction coefficient, taken as 0.85 in this study.

The above evaluation indices are methods for judging the activation of relevant potential faults by using the stress state on the fault plane. When the maximum shear stress acting on the fault plane exceeds the shear strength of the fault plane, the fault will be activated and become unstable, inducing microseisms and causing a series of safety problems. The shear stress on the fault plane is shown in Fig. 9, and measurement point P is selected to calculate the fault stability. For the numerical model in this study, because it is affected by the periodic injection and production of the CAES underground cavern, the maximum value of the slip tendency over one cycle is taken, $T_s = 0.608$, and the minimum value of the safety factor is FOS = 1.397.

Fig. 9 Shear stress cloud diagram when running for one cycle

3.3 Sensitivity Analysis of Fault-Stability Parameters

It is not difficult to see from Eq. (14) and Eq. (15) that, when evaluating fault stability, the main influences are the stress field and pore-pressure field in the fault region. In specific engineering terms, these correspond to the CAES injection rate, cycle period, fault dip angle, burial depth, and so on.

Only the CAES gas injection rate is changed, while the other parameters remain unchanged. The fault slip tendency T_s and safety factor FOS are shown in Fig. 10.

Fig. 10 Influence of gas injection rate on sliding tendency and safety factor

As the gas injection rate increases, the fault slip tendency T_s linearly

increased from 0.608 to 0.613; the fault safety factor FOS decreased linearly, from 1.397 to 1.386. Judging from the magnitudes of these changes, the influence of the gas-injection rate on fault stability is relatively small, and the selection of the gas-injection rate is more affected by the pressure-bearing capacity of the gas storage reservoir.

Figure 11 shows the influence of the CAES cycle period on the fault sliding trend T_s and the safety factor FOS. As the cycle period increases, the fault sliding trend T_s increases linearly, from 0.61 to 0.83; the fault safety factor FOS decreases linearly, from 1.39 to 1.02. The influence of the CAES cycle period is greater than that of the gas-injection rate. With an increase in the cycle period, the tendency for fault activation increases, while the stability of the gas storage reservoir continues to decline. For the service life of the gas storage reservoir, the effects of both factors must be comprehensively considered so as to avoid major safety accidents.

Fig. 11 Influence of the cycle period on the sliding trend and safety factor

Fig. 11 The influence of the cycle period on the sliding trend and safety factor

The increases in gas-injection rate and cycle period cause fluid to seep into the fault, increasing the pore pressure inside the fault. As shown in Fig. 12(a), with the increase in cycle period, the pore pressure increases linearly, from 1.935 MPa to 2.474 MPa. According to the effective-stress principle, the effective stress inside the fault decreases; as the cycle period increases, the effective stress decreases linearly, from 2.952 MPa to 2.852 MPa. In terms of the Mohr stress circle, as shown in Fig. 12(b), an increase in pore pressure reduces the effective stress, causing the Mohr stress circle to shift leftward and become tangent to the fault failure envelope, thereby inducing fault activation.

Figure 13 shows the influence of fault dip angle on the fault sliding trend T_s and the safety factor FOS. As the fault dip angle increases, at 70° the fault sliding trend T_s reaches its minimum value of 0.54, while the fault safety factor FOS reaches its maximum value of 1.57. With increasing fault dip angle, the variation trends of the fault sliding trend T_s and the safety factor FOS are parabolic. According to the three-dimensional stress equation [30], $\tau = \frac{(\sigma_1 - \sigma_3)}{2} \sin 2\theta$, where θ is the angle between the fault normal and the maximum principal stress. The smaller the fault dip angle, the greater the shear stress on the fault, and the more readily fault activation occurs.

Figure 14 shows the influence of burial depth on the fault sliding trend T_s and the safety factor FOS. At 150–200 m, the fault sliding trend T_s increases markedly, from 1.8 to 6.9; at 50–100 m, the fault safety factor FOS decreases sharply, from 9.4 to 1.4. Burial depth changes the ratio of horizontal to vertical in-situ stress at the fault location. As burial depth increases, the vertical stress increases and the horizontal stress decreases, weakening the restraining effect on shear slip along the fault. With increasing burial depth, the fault sliding trend T_s increases exponentially, while the fault safety factor FOS decreases exponentially. The smaller the burial depth, the greater the stability of the fault; however, for the gas storage reservoir, the stability of the cavern decreases substantially.

Fig. 12(a) Variation trends of fault pore pressure and effective stress with cycle period
Legend: pore pressure; effective stress. Axes: pore pressure/MPa; effective stress/MPa; cycle period.

Fig. 12(b) Schematic of the principle
Labels: shear stress; effective stress; fault failure envelope; $\tau = \sigma \tan \varphi$; pore pressure increases; $\sigma_n - p_f$.

Fig. 12 Increase in pore pressure induces fault instability

Fig. 12 The increase of pore pressure induces fault instability

Fig. 13 Influence of fault dip angle on sliding trend and safety factor

Fig. 13 The influence of fault dip angle on sliding trend and safety factor

Fig. 14 The influence of buried depth on sliding trend and safety factor

4 Conclusions

In this study, a numerical model containing a faulted surrounding rock mass was established. Through evaluation criteria for the stability of the underground cavern and fault activation, the stability of both and the influence of sensitive parameters on them were analyzed. The main conclusions are as follows.

1) During a single cycle period, both excavation damage and the fault enhance the maximum radial displacement of the cavern sidewall, but the fault has a greater influence on the maximum radial displacement of the cavern sidewall. Excavation damage increases and amplifies the maximum radial displacement at the cavern crown; after 30 cycles, the increment of the maximum radial displacement at the crown is 0.82 mm, which promotes uplift failure of the ground surface. By contrast, the fault reduces the displacement at the cavern crown and resists uplift failure of the ground surface.

2) The operating parameters of the CAES gas-storage cavern, namely the injection rate and cycle period, have relatively small effects. As the injection rate and cycle period increase, the fault sliding tendency T_s increases linearly, while the fault safety factor FOS decreases linearly. For the service life of the gas-storage cavern, the effects of fault activation and the cycle period must be considered comprehensively to avoid major safety accidents.

3) Among the four sensitive parameters for fault stability, buried depth has the greatest influence, followed by fault dip angle, while the injection rate has the smallest influence. When the fault dip angle is 70°, the stability of the fault is the greatest, reaching the peak point of the parabola. As buried depth increases, the fault sliding tendency T_s grows exponentially, while the fault safety factor FOS decreases exponentially.

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Note: Figure translations are in progress. See original paper for figures.