Study on the sensitivity of injection-production parameters for the long-term safety and stability of salt cavern gas storage

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Research Article

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Abstract

Injection-production operation parameters such as the minimum injection gas pressure (IGP: operation pressure), IGP interval, minimum IGP residence time and injection-production cycle period of long-term operation of underground salt rock gas storage will not only affect the storage capacity and working ability of gas storage but also be crucial to the safety and stability of the surrounding rock. A 3D geomechanical model of a salt cavern was established by WinUbro to study the stability of gas storage in the operation period. Five evaluation criteria for predicting the feasibility and stability of gas storage were comprehensively considered, including deformation, expansion safety factor, volume shrinkage, plastic zone and sensitivity. The stability of the surrounding rock of the cavern under different injection-production operation parameters and the degree of influence of each parameter on the stability of gas storage during the operation period are compared. The results show that the displacement of the surrounding rock and its deformation distribution range, the displacement of the roof of the cavern, the expansion coefficient of the surrounding rock of the salt cavern and the volume shrinkage rate of the salt cavern decrease significantly with the injection-production operation parameters. The plastic zone of the salt cavern increases with the rise in the IGP interval and the increase in the minimum IGP; however, the minimum IGP residence time and injection-production period have no obvious influence on the plastic zone of the salt cavern. The IGP interval and the minimum IGP have a positive influence on the plastic zone of the salt cavern, however, the minimum IGP residence time and injection-production period have no obvious influence on the plastic zone. The sensitivity coefficients of each injection-production operation parameter are ranked, from
largest to smallest, as follows: IGP interval, minimum IGP, minimum IGP residence time and injection-production cycle. This conclusion can provide a theoretical basis for further optimizing the operation scheme design of salt rock gas reservoirs and ensuring the safety and stability of the long-term injection-production process of layered salt rock gas storage.

**Keywords:** Safety engineering; Injection-production operation; Stability; Sensitivity; Numerical simulation

**Abbreviations**

IGP: injection gas pressure
1 Introduction

In recent years, China’s dependence on foreign natural gas has gradually increased (Fig. 1), making China’s energy security situation increasingly serious [1]. Due to the excellent creep properties, anti-permeability, plastic deformation capacity and recovery performance of salt rock, it has become an ideal place for energy storage [2–4]. However, due to the long-term operation of gas storage in salt rock in the past three decades, the creep of salt rock caused by improper internal pressure control has caused catastrophic accidents, including fires and explosions, cavern failure and surface subsidence of the reservoir area. Such accidents can be sudden and destructive, posing a large danger to safety and the environment (Table 1) [5–9]. For example, in the 1990s, the Stratton Ridge gas storage in Texas collapsed, it was scrapped due to the excessive creep of salt rock and the presence of salt rock formations in wet terrain, which created unsafe conditions for the injection-production process and resulted in huge economic losses. In 2001, the working Yaggy gas storage in Kansas collapsed during gas injection-production, leading to hundreds of people lost their lives due to fires and explosions caused by oil and gas leakage. According to the investigations, the reasons behind the above accidents were related to unreasonable operation parameters. The controllable injection-production operation parameters of gas storage include the injection gas pressure (IGP) interval, minimum IGP, minimum IGP residence time, injection-production cycle, etc. When the IGP interval increases, the internal pressure limit remains unchanged but the range increases close to that of the original rock (before a cavern was built), thus the cavern will be more stable. The increase in the minimum internal pressure reduces the internal pressure difference. A smaller internal pressure difference
leads to a more stable cavern but also a greatly reduced economic benefit. Since the demand for
natural gas is related to seasonal changes, the low-pressure residence time and
injection-production cycle should be adjusted accordingly. The rational allocation of parameters
can not only increase the storage capacity and the working capacity of gas storage but also
reduce the occurrence of disasters. Thus, the study of injection-production operation parameters
is of great significance to the stability of layered salt rock gas storage.

![Graph showing consumption, production, and dependence of natural gas in China](image)

**Fig. 1.** The consumption, production and dependence of natural gas in China [31]

<table>
<thead>
<tr>
<th>Name of storage cavern</th>
<th>Time and place of accident</th>
<th>Accident description</th>
<th>Accident cause</th>
<th>Economic loss</th>
<th>Influence scope</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kiel</td>
<td>1967, Germany</td>
<td>12.3% loss in volume after 45 days</td>
<td>Excessive creep of salt</td>
<td>Cavern failure</td>
<td>The cavern</td>
</tr>
<tr>
<td>Eminence</td>
<td>1970-1972, Mississippi, USA</td>
<td>More than 40% loss of volume</td>
<td>Excessive creep of salt</td>
<td>Cavern failure</td>
<td>The cavern</td>
</tr>
<tr>
<td>Tersanne</td>
<td>1970-1980, France</td>
<td>Effective volume loss 35%, settlement rate 40 mm/a</td>
<td>Excessive creep of salt</td>
<td>Cavern deactivated</td>
<td>Influence range approximately 2000 m</td>
</tr>
<tr>
<td>Stratton</td>
<td>1990s,</td>
<td>Cavern abandoned, ground</td>
<td>Excessive</td>
<td>Cavern</td>
<td>Ground</td>
</tr>
</tbody>
</table>
Table 1. Typical gas storage accidents

<table>
<thead>
<tr>
<th>Location</th>
<th>Year, Country</th>
<th>Event</th>
<th>Cause</th>
<th>Consequences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ridge</td>
<td>Texas, USA</td>
<td>subsidence, settlement</td>
<td>40 mm/a</td>
<td>Failure of salt and in wet condition above the caverns</td>
</tr>
<tr>
<td>Yaggy</td>
<td>2001, Kansas, USA</td>
<td>Fire &amp; explosion</td>
<td>Failure of piping and damage of casing during injection</td>
<td>About 5600,000 m³ natural gas loss</td>
</tr>
<tr>
<td>Moss Bluff</td>
<td>2004, Texas, USA</td>
<td>Fire &amp; explosion</td>
<td>Brine pipe corrosion</td>
<td>At least 36 million US $ loss</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Influence range was 120 m, people within 5 km evacuated</td>
</tr>
</tbody>
</table>

Much research has been done on evaluating the stability of layered salt rock gas reservoirs, and great progress has been made. In 1989, Schmidt determined the minimum internal working pressure of salt rock gas storage and found that when a gas storage has a long operational period, if the cavern volume of the gas storage was decreasing, the cavern would eventually become unusable [10]. In 2002, Bruno studied the method to determine the ultimate operating pressure of gas storage. It was found that the sidewall and roof of layered salt rock gas storage may collapse during operation, and the ultimate operating pressure of gas storage depends on the geological conditions and mechanical properties of salt rock [11]. Michael and Maurice simplified the interlayer at the top of the gas storage into a composite beam structure to determine the minimum working pressure. In 2004, Liu et al. [12] determined the operating pressure of a gas storage in a thin salt layer by analytical methods and numerical analysis. In 2005, Yang et al. [13] established a Cosserat medium expansion constitutive model considering the meso-bending effect in the macroaverage sense to numerically simulate different internal pressures and obtained the corresponding optimal operating pressure. In 2006, Chen et al. [14]...
established a numerical model of Jintan salt rock gas storage to study the creep deformation and plastic damage zone of salt rock and proposed an acceptable internal gas operating pressure and casing shoe depth. In 2008, Liang et al. [15] obtained the ultimate operating pressure of gas storage by studying the physical and mechanical properties of layered salt rock gas storage. Cao established the injection-production dynamic model of underground salt rock gas storage, studied the operation characteristics of cyclic injection-production, and determined the operation parameters [16]. In 2012, Zhang et al. [17] studied the influence of risk factors such as the gas injection-production rate, operation pressure and gas storage spacing on the operation safety and stability of layered salt rock gas storages system through a 3D rheological geological model. Ji studied the deformation law of underground salt rock gas storage under different injection-production schemes for 30 years. It was found that the shape of underground salt rock gas storage had little effect on the stability of gas storage. The low-pressure operation period after emergency gas recovery was the main stage of volume convergence of underground gas storage [18]. In 2014, Zhang studied the long-term stability of underground salt rock gas storage with interlayers under different internal pressure conditions and determined that the influence of operating pressure on the shrinkage of gas storage was greater than that of interlayers [19]. In 2016, Wang et al. [20] studied the minimum internal operation pressure of multilayer gas storage. It was found that increasing the span and depth of the top of the gas storage can increase the minimum allowable operating pressure. The increase in the elastic modulus of the adjacent interlayer at the top of the gas storage leads to a decrease in the minimum allowable pressure. In 2017, Ma et al. [21] established underground salt rock gas storage models with different internal
operating pressures and different hole diameter ratios to determine the optimal values. In 2018, Wang et al. [22] established a 3D geomechanical model of JK-A gas storage to study the stability of the roof of the gas storage and determined that the roof collapse of JK-A gas storage is related to the operation pressure and rate of pressure decrease. Zhang et al. [23] proposed a method for determining the upper and lower limits of operating pressure. In 2019, Liu studied the stress of the cavern wall under different injection-production rates. It was concluded that rapid injection-production leads to tensile stress increasing, and there are clear tensile stress zones at the top and bottom of the cave [24]. Wang et al. [25] established a 3D geomechanical model based on the sonar data of Jintan Gas Storage combined with the characteristics of the target stratum and concluded that the King-1 cavern was safe by international standards when the maximum operating pressure increased from 17 MPa to 18 MPa. In 2020, the thermomechanical model proposed by Li provided a method for evaluating the long-term stability of underground rock salt caverns and was used to determine the optimal operating parameters and salt cavern design [26]. Artur A. Makhmutov used a 2D finite element model with unstructured grids to model and simulate the complex creep behaviour of rock salt caves, which helped to evaluate the long-term safety and reliability of the roof structure. A sensitivity analysis of key parameters was carried out to understand the influence of creep on the deformation and stress evolution around the roof structure of salt caves [27].

In summary, there is little research related to the sensitivity of injection-production operation parameters in the operation period of gas storage, which is necessary for the optimization of the parameters. Therefore, this paper summarizes and analyses the stability of
surrounding rock of a salt cavern under different injection-production operation parameters: the minimum IGP, IGP interval, minimum IGP residence time, and injection-production cycle. The following four evaluation criteria are used to predict the stability and feasibility of the salt cavern: the deformation, expansion safety factor, volume shrinkage and plastic zone. Then, the sensitivity of the safety and stability of the gas storage to the injection-production operation parameters is studied. This paper can provide a theoretical basis and technical guidance for the design, construction and operation of salt rock gas storage.

2 Safety and Stability Evaluation Index of Gas Storage

To evaluate the stability of salt rock gas storage during operation, the surrounding rock deformation, cavern volume shrinkage, expansion safety factor and plastic zone volume are introduced and comprehensively counted as stability indices to evaluate the safety of gas storage (Table 2). These evaluation indices consider the influence of creep, shear, tension, expansion and shrinkage on the stability of gas storage during operation and are widely used for the stability evaluation of salt rock gas storage. The following four indicators are explained and discussed.

<table>
<thead>
<tr>
<th>Index</th>
<th>Author</th>
<th>Year</th>
<th>Criterion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Displacement</td>
<td>Yang et al. [28]</td>
<td>2009</td>
<td>The maximum displacement of caverns should not exceed 5% of the maximum cavern diameter</td>
</tr>
<tr>
<td></td>
<td>Zhang et al. [29]</td>
<td>2017</td>
<td>The maximum displacement of single-well-vertical (SWV) caverns should not exceed 10% of the maximum cavern diameter</td>
</tr>
<tr>
<td></td>
<td>Wang et al. [25]</td>
<td>2018</td>
<td>The maximum displacement of single-well-vertical (SWV) caverns should not exceed 5% of the maximum cavern diameter</td>
</tr>
<tr>
<td></td>
<td>Chen et al. [30]</td>
<td>2020</td>
<td>The maximum displacement of small-spacing two-well (SSTW) should not exceed 5% of the maximum cavern diameter</td>
</tr>
<tr>
<td>Dilatancy safety factor</td>
<td>Li et al. [31]</td>
<td>2021</td>
<td>The maximum displacement of U-shaped horizontal (UHSC) caverns should not exceed 7% of the maximum cavern diameter</td>
</tr>
<tr>
<td>-------------------------</td>
<td>----------------</td>
<td>------</td>
<td>------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Spiers et al. [32]</td>
<td>1989</td>
<td>$\sqrt{J_2} = 0.27I_1 + 1.9$</td>
<td></td>
</tr>
<tr>
<td>Ratigan et al. [33]</td>
<td>1991</td>
<td>$\sqrt{J_2} = 0.27I_1$</td>
<td></td>
</tr>
<tr>
<td>Hunsche [34]</td>
<td>1993</td>
<td>$\sqrt{J_2} = -2.286 \times 10^3 \times I_1^2 + 0.351 \times I_1$</td>
<td></td>
</tr>
<tr>
<td>Spiers et al. [32]</td>
<td>2004</td>
<td>$\sqrt{J_2} = 12.04 - 9.104e^{-0.0493I_1}$</td>
<td></td>
</tr>
<tr>
<td>Alkan et al. [35]</td>
<td>2007</td>
<td>$\sqrt{J_2} = \frac{0.54I_1}{1 + 0.013I_1}$</td>
<td></td>
</tr>
<tr>
<td>Labaune and Rouabhi [36]</td>
<td>2018</td>
<td>$\sqrt{J_2} = 0.25I_1 + 1.44$</td>
<td></td>
</tr>
<tr>
<td>Volume shrinkage</td>
<td>Bérest and Minh [37]</td>
<td>1981</td>
<td>30-year volume shrinkage of gas storage $\leq 30%$</td>
</tr>
<tr>
<td>Hou and Wu [38]</td>
<td>2003</td>
<td>30-year volume shrinkage of gas storage $\leq 20%$</td>
<td></td>
</tr>
<tr>
<td>Brouard et al. [49]</td>
<td>2012</td>
<td>1-year volume shrinkage $\leq 1%$, 30-year volume shrinkage $\leq 30%$</td>
<td></td>
</tr>
<tr>
<td>Liu et al. [40]</td>
<td>2018</td>
<td>1-year volume shrinkage $\leq 1%$, 5-year volume shrinkage $\leq 5%$, 30-year volume shrinkage $\leq 30%$</td>
<td></td>
</tr>
<tr>
<td>Chen et al. [30]</td>
<td>2020</td>
<td>1-year volume shrinkage $\leq 1%$, 30-year volume shrinkage $\leq 30%$</td>
<td></td>
</tr>
<tr>
<td>Plastic zone</td>
<td>Wang et al. [41]</td>
<td>2015</td>
<td>$f' = \sigma_1 - \frac{1 + \sin \phi}{1 - \sin \phi} \sigma_3 - \frac{2c \cdot \cos}{1 - \sin \phi}, \quad f' = \sigma_r - \sigma_s$</td>
</tr>
<tr>
<td>Ma et al. [42]</td>
<td>2015</td>
<td>$f' = \sigma_1 - \frac{1 + \sin \phi}{1 - \sin \phi} \sigma_3 - \frac{2c \cdot \cos}{1 - \sin \phi}, \quad f' = \sigma_r - \sigma_s$</td>
<td></td>
</tr>
<tr>
<td>Yang et al. [43]</td>
<td>2016</td>
<td>(\frac{1}{2}(\sigma_1 - \sigma_3) = C \cos \phi - \frac{1}{2}(\sigma_1 + \sigma_3) \sin \phi)</td>
<td></td>
</tr>
<tr>
<td>Zhang et al. [29]</td>
<td>2017</td>
<td>(\frac{1}{2}(\sigma_1 - \sigma_3) = C \cos \phi - \frac{1}{2}(\sigma_1 + \sigma_3) \sin \phi)</td>
<td></td>
</tr>
<tr>
<td>Liu et al. [44]</td>
<td>2020</td>
<td>$f' = \sigma_1 - \frac{1 + \sin \phi}{1 - \sin \phi} \sigma_3 - \frac{2c \cdot \cos}{1 - \sin \phi}, \quad f' = \sigma_r - \sigma_s$</td>
<td></td>
</tr>
</tbody>
</table>

**Table 2.** Evaluation Index of Gas Storage Stability

2.1 **Surrounding rock deformation**

Surrounding rock deformation, especially roof subsidence, is an important index reflecting the
stability of salt rock gas storage and is easy to monitor in simulations [25,28,30]. Through the
distribution of the surrounding rock displacement, the deformation of each position of the salt
cavern can be clearly seen, and an optimal shape can more easily be determined. Research shows
that the maximum displacement of the surrounding rock of gas storage should meet the following
criteria:
\[ D_{\text{max}} \leq 5\%d_{\text{max}} \]  \hspace{1cm} (1)
where \( D_{\text{max}} \) is the maximum displacement and \( d_{\text{max}} \) is the maximum salt chamber diameter.

2.2 Expansion safety factor

The expansion safety factor is an important indicator of many practical engineering applications.
When the rock is in a complex stress state, expansion failure may impacting the dynamic sealing
capacity of the storage and cause leakage of the gas. Therefore, damage due to the expansion of
salt rock must be avoided during the long-term injection and production operation of the gas
storage. Referring to the research of Spiers et al. [32], Ratigan et al. [33], and Hunsche [34] (Fig.
2), the expansion failure criterion of salt rock is established as follows:
\[ SF = \frac{\sqrt{J_2}}{aI_1 + b} \geq 1 \]  \hspace{1cm} (2)
where \( SF \) is the safety factor; \( a, b \) are the coefficients of expansion, subject to test fitting; \( I_1 \) is the
first stress invariant; and \( J_2 \) is the second stress deviation invariant. \( I_1 \) and \( J_2 \) can be
calculated by Equations (3) and (4):
\[ I_1 = \sigma_1 + \sigma_2 + \sigma_3 \]  \hspace{1cm} (3)
\[ J_2 = \frac{1}{6} \left[ (\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 \right] \] (4)

where \( \sigma_1 \), \( \sigma_2 \) and \( \sigma_3 \) are the minimum, intermediate and maximum principal stresses, respectively.

**Fig. 2.** Expansion failure criterion of salt rock [33]

### 2.3 Volume shrinkage of the cavern

Salt cavern volume shrinkage is an important index to evaluate the availability and economy of salt rock gas storage. It is defined as the ratio of the volume reduction to the original volume of the salt cavern. According to reference [39], in China, the volume shrinkage rate of salt rock gas storage should satisfy the following:

\[ \frac{V - V_t}{V} \times 100\% \leq 20\% \] (5)

where \( V \) is the original volume of the salt cavern and \( V_t \) is the current volume of the salt cavern.

### 2.4 Plastic zone volume
The failure modes of salt rock mainly include shear failure and tensile failure. The plastic failure of the rock mass around the salt cavern is determined by criterions that provided within FLAC$^{3D}$ software, Mohr–Coulomb criterion (6) and the maximum tensile stress criterion (7). Many publications use this criterion as an indicator, and it has proven to be accurate and reliable [29].

\[
f' = \sigma_1 - \frac{1 + \sin \varphi}{1 - \sin \varphi} \sigma_3 - \frac{2c \cdot \cos \varphi}{1 - \sin \varphi}
\]

\[
f' = \sigma_1 - \sigma_3
\]

where $\sigma_1$ is the minimum principal stress, $\sigma_3$ is the maximum principal stress, $c$ is the cohesion, $\varphi$ is the internal friction angle, and $\sigma_t$ is the tensile strength of the rock mass.

As shown in Fig. 3, the failure criterion in FLAC$^{3D}$ divides the stress space into three areas: Area 1 is the tensile failure zone, Area 2 is the shear failure zone and Area 3 is the nonfailure zone. The volume of the plastic zone is equal to the sum of the shear failure zone and tensile failure zone.

![Mohr–Coulomb failure criterion](image)

**Fig. 3.** Mohr–Coulomb failure criterion [42]

• When $\sigma_3 > \sigma_1$, if the shear failure function $f^S > 0$, the stress state is located in Area 2.

Otherwise, the stress state is located in Area 1, and no damage will occur.
When $\sigma_3 < \sigma_1$, the stress state is located in Area 3, and tensile failure occurs.

3 Numerical Calculation

3.1 3D geomechanical model and its boundary conditions

By modelling a layered salt rock gas storage, the influence of injection-production operation parameters on the operation period of underground gas storage with interlayers is studied. Interlayers in the stratum of the reservoir area are unevenly distributed with thicknesses ranging from 1 m to 14 m. Based on the actual geological conditions of the project, the cavern is simulated by WinUbro (Fig. 4) and its 3D axisymmetric mechanical model is established by FLAC$^3$D. The cavern height is 150 m, maximum diameter is 76 m, effective volume is $33.6 \times 10^4$ m$^3$, XY plane range 800 m×800 m, and the vertical plane is defined in the Z axis direction. The weight of the overlying rock is equivalent to the upper surface load of the cube model, and the equivalent load is calculated according to the actual thickness and average density ($2.63 \times 10^3$ kg/m$^3$) of the stratum. The undersurface of the model cube is unidirectionally constrained in the Z direction, and the longitudinal surface is simply supported in the normal direction perpendicular to the surface (Fig. 5).
Fig. 4. Simulation result

(a) Geological profile
3.2 Design of the gas injection-production operation scheme

According to the documents “Design Specification of Salt Rock Gas Storage Cavern” and “Safety Specification For Salt Rock Underground Gas Storage” [45,46] and logging data, the upper limit pressure should not exceed 80% of the overlying strata pressure and fracture pressure.
Considering the roof quality, the maximum operating pressure of the salt cavern is designed to be 13 MPa. Referring to the pressure gradient of the lower limit pressure of Jintan gas storage of 0.7 MPa/100 m and considering the gas recovery capacity of the salt cavern, wellhead pressure, salt cavern stability and other factors, the minimum pressure of salt cavern operation is determined to be 4 MPa. Therefore, the design IGP range is 4 MPa~13 MPa.

To research the stability of the rock mass around the cavern under different injection-production operation parameters, referring to China's existing Jintan gas storage operation scheme [47,48] and China's market demand [49], a numerical calculation scheme is designed, as shown in Table 3. The variation of operating pressure in different schemes for one year is shown in Fig. 6 considering the following: the continuous injection-production of gas storage is stable for 30 years and the complete injection-production operation cycle is 1 year, which is calculated as 365 days with 1 step-down gas recovery, 1 step-down gas injection and 2 stable pressure shut-ins.

<table>
<thead>
<tr>
<th>Simulation number</th>
<th>a (Benchmark plan)</th>
<th>b</th>
<th>c</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x_1$ (IGP range; MPa)</td>
<td>5-12</td>
<td>4-11</td>
<td>6-13</td>
</tr>
<tr>
<td>$x_2$ (Minimum operating IGP; MPa)</td>
<td>5-12</td>
<td>4-12</td>
<td>6-12</td>
</tr>
<tr>
<td>$x_3$ (Dwell time of the minimum IGP; day/year)</td>
<td>46</td>
<td>26</td>
<td>36</td>
</tr>
<tr>
<td>$x_4$ (Cycle IGP; cycles/year)</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
</tbody>
</table>

**Table 3.** Comparison scheme design of various influencing parameters

![Graphs](image-url)
Fig. 6. Operating pressure of the salt cavern

\( x_1 \): Fig. 6(a) shows the injection-production operating pressure changes over 1 year considering an overall increase in IGP interval, that is, the designed IGP ranges are, sequentially, 4-11 MPa, 5-12 MPa, and 6-13 MPa.

\( x_2 \): Fig. 6(b) shows the injection-production operating pressure changes over 1 year considering an unchanged upper limit of IGP and an increase in the lower limit of IGP, that is, the designed IGP range are 4-12MPa, 5-12MPa, and 6-12MPa.

\( x_3 \): Fig. 6(c) shows the injection-production operating pressure changes over 1 year considering different residence times of the minimum IGP, that is, the designed residence times of the minimum IGP are 26 days, 36 days, and 46 days.

\( x_4 \): Fig. 6(d) shows the injection-production operating pressure changes over 1 year considering different injection-production cycles, that is, the designed injection-production cycles are once a year, twice a year and three times a year.

3.3 Select calculation parameters

The salt layer in the reservoir area is mainly composed of salt rock, salt-bearing calcium
mirabilite interlayers and mudstone. Rock mechanical parameters were determined by routine laboratory creep tests and are given in Table 4. Long-term stability analysis of salt rock gas storage using the Cpower creep constitutive model in FLAC$^{3D}$, The model includes Norton and Mohr–Coulomb models, and the steady-state creep rate obeys the Norton energy law. The standard form of the Norton exponential model is shown in Equation (8):

$$
\dot{e}(t) = A q^n
$$

(8)

where $\dot{e}(t)$ is the steady-state creep rate; $J_2$ in $q = \sqrt{3J_2}$ is the second invariant of the deviatoric stress; $A$ is the material characteristic parameter; and $n$ is the constant of the stress index.

<table>
<thead>
<tr>
<th>Property</th>
<th>Material</th>
<th>Rock salt</th>
<th>Mudstone</th>
<th>Interlayer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s modulus (GPa)</td>
<td></td>
<td>6.84</td>
<td>22.9</td>
<td>38.5</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td></td>
<td>0.21</td>
<td>0.15</td>
<td>0.20</td>
</tr>
<tr>
<td>Cohesion (MPa)</td>
<td></td>
<td>8.40</td>
<td>7.75</td>
<td>5.80</td>
</tr>
<tr>
<td>Friction angle (Deg)</td>
<td></td>
<td>39.3</td>
<td>45.4</td>
<td>46.9</td>
</tr>
<tr>
<td>Tensile strength (MPa)</td>
<td></td>
<td>1.38</td>
<td>3.19</td>
<td>1.42</td>
</tr>
<tr>
<td>A(creep model) (MPa•h$^{-1}$)</td>
<td></td>
<td>9.0×10$^{-7}$</td>
<td>2.8×10$^{-6}$</td>
<td>2.8×10$^{-6}$</td>
</tr>
<tr>
<td>n(creep model)</td>
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Table 4. Rock mechanical parameters

4 Influence of Injection-production Operation Parameters on Stability of Gas Storage

For different schemes of injection-production operation parameters, a study was performed based on (1) the mechanical behaviour of the surrounding rock after 30 years of operation (including deformation, expansion failure, volume shrinkage and plastic zone formation) and (2) the
sensitivity of gas storage safety and stability to injection-production operation parameters (IGP interval, minimum IGP, minimum IGP residence time, injection-production cycle). The flow chart of the gas storage stability assessment and the selected injection-production operation parameters are shown in Fig. 7.

![Flow chart of gas storage stability assessment](image)

**Fig. 7.** Flow chart of gas storage stability assessment

### 4.1 Deformation Law of Surrounding Rock in Salt Cavern

Fig. 8 shows the contours of the surrounding rock deformation after 30 years of gas production by different schemes. After 30 years of operation, the deformation of the surrounding rock is generally distributed in layered diffusion, and the deformation decreases with distance away from the cavern wall. The maximum displacement occurs at the cavern wall of the gas storage, and the maximum displacement of 1.78 m is 2.3% of the maximum diameter of the salt cavern (76 m). The displacement and deformation distribution range of the surrounding rock decrease
significantly with increasing IGP interval and minimum IGP but it increase with increasing minimum IGP residence time and injection-production cycle.

(a) $x_1$

(b) $x_2$

(c) $x_3$
Fig. 8. Total deformation contours with different schemes after 30 years of operation.

Fig. 9 shows the displacement of the cavern top plate in different schemes for 30 years. The deformation of the roof in different schemes increases in a step-by-step fluctuation with the passage of time, and the curve slope decreases year by year. This is due to the alternating effect of high and low pressure during injection and production in the operation period of gas storage, but its impact slows over time.
In scheme X1, the displacement of the cavern top plate with the IGP range of 4-11 MPa after 30 years of injection-production operation increased by 13.85% compared with that of (under suitable) the 5-12 MPa range (benchmark plan), while the displacement of the cavern top plate in the IGP range of 6-13 MPa decreased by 12.14% compared with that of the 5-12 MPa range. This is because when the pressure operation range increases, the equivalent internal pressure limit difference remains unchanged, but the range increases, close to the original rock stress level before cavern construction, and thus the cavern is more stable.

In the X2 scheme, the displacement of the cavern top plate increased by 8.81% when the minimum IGP was 4 MPa, and the displacement of the cavern top plate decreased by 8.0% when the minimum IGP was 6 MPa. The reason is that increasing the minimum range pressure reduces the internal pressure limit difference, and the surrounding rock of the cavern is weakened by creep.

In the X3 scheme, when the low-pressure residence time was 26 days and 36 days, the
displacement of the cavern roof was reduced by 4.77% and 2.34%, respectively, after 30 years of injection-production operation compared with 46 days (benchmark plan). This is because the pressure of the cavern is unstable when the gas storage cavern is in a low-pressure state, so the long time in a low-pressure state will affect the displacement of the cavern roof.

In the X4 scheme, the displacement of the cavern top plate increased by 1.71% and 3.51%, respectively, after two and three injection-production cycles in one year compared with once a year. Therefore, in general, the minimum IGP decreases significantly as the IGP interval increases, while it increases with the minimum IGP residence time and injection-production cycle.

4.2 Expansion safety factor

Using Equation (2), the isoline of the expansion safety factor around salt rock gas storage under different schemes after 30 years is obtained (Fig. 10). Fig. 10 shows that the expansion coefficients of the surrounding rock of the salt cavern are all less than 1; that is, there is no expansion failure phenomenon in the salt rock. The safety factor of the surrounding rock of the overall cavern wall of the gas storage is small, but the safety factor of the interlayer of the cavern wall is large. This is because the layered sedimentary structure of the interlayer has high strength, and its existence has an effective constraint on the salt rock, which is conducive to the stability of the gas storage. In short, the expansion coefficient of the salt cavern’s surrounding rock increases significantly with increasing IGP range and increasing minimum IGP while it decreases with increasing minimum IGP residence time and injection-production cycle.
Fig. 10. Safety factor (SF) isolines of gas storage after 30 years of operation of different schemes (after gas production)

4.3 Trend of salt cavern volume

Fig. 11 shows the volume shrinkage rates of the salt cavern in different schemes for 30 years. The volume shrinkage in each scheme after 30 years of operation is less than 20%, which can meet the empirical requirements of storage stability. The volume shrinkage rates of salt chambers in different schemes increase step-by-step with time, and the slope of the curve decreases year by year. The volume shrinkage rate of the salt cavern decreases significantly with increasing IGP interval and minimum IGP while it increases with increasing minimum IGP residence time and injection-production cycle.
4.4 Plastic zone

The appearance of the plastic zone actually refers to shear failure and/or tensile failure in the surrounding rock. These failures indicate that the unit has irreversible plastic deformation, and the macro shows the initiation and propagation of cracks. Therefore, to compare the effects of different schemes, the volume of the plastic zone is statistically analysed.

Table 5 shows the variation in the plastic zone in different gas storage schemes. Fig. 12 shows
the ratio of the plastic zone volume to the salt cavern volume of different schemes for 30 years.

Together, Table 5 and Fig. 12 show that the plastic zone of the surrounding rock of the gas storage increases first and then decreases with the passage of time. This is because the stress of the salt rock mass is in the initial period of creep in the water solution cavern stage and the early stage of gas storage operation. The plastic deformation increases gradually with increasing time. When the shear stress exceeds the strength of the salt rock, the plastic zone develops. With the increase in operation time, the salt rock creep stabilizes; at this time, the salt rock creep rate is less than that at the initial creep stage, and the plastic zone decreases. The plastic zone of the surrounding rock increases with the rise of the IGP interval and the increase of the minimum IGP. The minimum IGP residence time and injection-production cycle have no obvious influence on the plastic zone.

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Table 5. The variation in the plastic zone in different gas storage schemes ($10^3$ m$^3$)
5 Sensitivity Analysis of Injection-production Operation Parameters

The sensitivity analysis method is used to study the influence of injection-production operation parameters on the stability of gas storage in the operation period. Sensitivity analysis methods are divided into single-factor sensitivity analysis and multifactor sensitivity analysis [50,51]. In this study, the single-factor sensitivity analysis method is used for dimensionless treatment of injection-production operation parameters. The curves of $F/F^*$ and $x_i/x^*$ ($i=1, 2, 3, \ldots, n$) are plotted in Fig. 13. The abscissa $x_i/x^*$ represents the ratio of the injection-production parameters of each model to the reference scheme, the ordinate $F/F^*$ represents the ratio of the system characteristics (top plate displacement, salt cavern volume shrinkage, and salt cavern plastic zone volume) of each model to the reference scheme, and the absolute value of the slope of the curve is defined as the sensitivity coefficient. The sensitivity coefficient reflects the influence of each injection-production parameter on the stability of the gas storage injection-production process. The greater the sensitivity coefficient is, the greater the influence of this parameter on the stability of the gas storage injection-production process.
Fig. 13. Sensitivity coefficient fitting curve

Fig. 14 shows a comparison of the sensitivity coefficients of the injection-production operation parameters. It can be seen from Figs. 13 and 14 that when only the influence of a certain system characteristic is considered, the top plate displacement, the volume shrinkage and the plastic zone of the salt cavern are significantly affected by the IGP interval ($x_1$) and to a lesser extent the minimum IGP ($x_2$). The residence time of the minimum IGP ($x_3$) and cycle IGP ($x_4$) have little effect on the plastic zone of the salt cavern. The sensitivity coefficients of each injection-production parameter are ranked as follows: IGP interval ($x_1$) > minimum IGP ($x_2$) > residence time of the minimum IGP ($x_3$) > cycle IGP ($x_4$). Compared with other injection-production parameters, the injection-production cycle ($x_4$) has less influence on the stability of gas storage during operation.

Fig. 14. Sensitivity coefficient comparison diagram

6 Conclusions
Through the influence of the minimum IGP, IGP interval, minimum IGP residence time and injection-production cycle on the safety and stability of layered gas storage in the operation period, the effect of injection-production operation parameters is determined. According to the comparison of numerical simulation schemes, the following conclusions are obtained:

1. The minimum IGP, IGP interval, minimum IGP residence time and injection-production cycle have an important impact on the safety and stability of gas storage and will lead to varying degrees of changes in the surrounding rock deformation, expansion safety factor, volume shrinkage and plastic zone of gas storage.

2. The displacement of the surrounding rock and its deformation distribution range, the displacement of the cavern roof, the expansion coefficient of the surrounding rock, and the volume shrinkage rate of the salt cavern all decrease significantly with the increase in the IGP interval, the increase in the minimum IGP, and the increase in the minimum IGP residence time and injection-production cycle. The plastic zone of the salt cavern increases with the increase in the IGP interval and the increase in the minimum IGP. The minimum IGP residence time and injection-production period have no obvious influence on the plastic zone of the salt cavern.

3. The sensitivity of the long-term operation of gas storage to different injection-production operation parameters is also different. When only the influence of a single system characteristic is considered, the displacement of the cavern roof, the volume shrinkage rate of the salt cavern and the plastic zone of the salt cavern are significantly affected by the IGP interval, followed by the minimum IGP. The minimum IGP residence time and injection-production cycle have no significant influence on the plastic zone of the salt cavern.
(4) The sensitivity coefficients of the comprehensive parameters are sorted as follows, in decreasing order of sensitivity: (1) IGP interval, (2) minimum IGP, (3) minimum IGP residence time, and (4) injection-production cycle. Therefore, considering the capacity of underground salt rock gas storage and to reduce the disaster risk, it is suggested that the operating pressure interval should be raised or the lower limit of operating pressure should be increased first, and then the duration of minimum operating pressure and injection-production cycle should be reduced.

Ethics declarations

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data Availability Statement

The data used to support the findings of this study are available from the corresponding author upon request.
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