Assessing the effect of intermediate principle geostress on the caprock integrity for underground gas storage

Zhechao Wang¹,²*, Xianxian Lyu¹,², Weichuan Shi¹,², Xia-ting Feng¹,², Liping Qiao¹,²

Rui Kong¹,²

¹ Key Laboratory of Liaoning Province on Deep Engineering and Intelligent Technology, Northeastern University, Shenyang, 110819, China.
² Key Laboratory of Ministry of Education on Safe Mining of Deep Metal Mines, School of Resources and Civil Engineering, Northeastern University, Shenyang, 110819, China.

*Corresponding author

Address:
Key Laboratory of Ministry of Education on Safe Mining of Deep Metal Mines, School of Resources and Civil Engineering, Northeastern University.
11#, 3rd Ave, Wenhua Rd
Shenyang, 110819, China
Telephone number: 86-24-83684891
Fax number: 86-24-83684690-9
Email: wang_zhechao@hotmail.com, wangzhechao@mail.neu.edu.cn
Abstract: It is of great significance to investigate the integrity of caprock for underground gas storage under 3D anistropic geostress conditions to increase the operation performance of depleted gas reservoir. A series of true triaxial compression tests were carried out on siltstone specimens of the caprock for a natural gas storage facility in Xinjiang province of China for modelling the elastoplastic behavior of the caprock. The constitutive model, named as Triple-Mean-Normal-Stress model (TMNS), is embedded into a FEM code to investigate the integrity of caprock for the storage. Mohr-Coulomb, Mogi-Coulomb and TMNS models were compared in analyzing the variations of pore pressure, stress and displacement in the reservoir during the gas injection stage. The results show that the rock at the interface of reservoir-caprock is more prone to damage during gas injection. The pore pressure and vertical displacement at the reservoir-caprock interface using the TMNS model are 3.01 MPa and 0.021 m less than those using the Mohr-Coulomb model, respectively. The integrity of the caprock for gas storage was evaluated, and the upper limit pressure for the storage at the critical failure state was formulated. When the caprock adopts TMNS model and uses TMNS damage criterion to determine if shear damage occurs in the rock, the reservoir will receive a greater upper limit pressure. Compared with the Mohr-Coulomb model, using the TMNS constitutive model, which considers the effect of intermediate principal stress, predicts a higher ultimate upper limit pressure of the gas storage by 13.7%. The research will enrich the basic theory of rock constitutive model, and provide a theoretical basis for the research on the integrity of caprock for gas storage and the geological storage of CO₂.

Keyword: Underground gas storage, 3D anistropic geostress, Integrity of caprock, Upper limit pressure
44 Highlights

45 • The effect of intermediate principle geostress on the caprock integrity is assessed.

46 • The variation of pore pressure, stress and displacement are analyzed during the gas injection stage.

48 • The integrity of the caprock is evaluated using tensile and shear failure criteria.

49 • The model considering intermediate principle stress can increase the ultimate upper limit pressure.
1 Introduction

The normal and safe operation of underground gas storage reservoirs is influenced by the hydraulic properties and integrity of the storage caprock. For depleted reservoirs and aquifer reservoirs, continuous injection of large quantities for natural gas into the geological reservoir may lead to damage to the integrity of caprock for underground gas storage, resulting in engineering geological hazards such as natural gas leakage and surface subsidence. The critical solution to these problems is to study the mechanisms by which damage occurs in the caprock of underground gas storage. Subsurface rocks are subject to unequal triaxial principal stresses \( \sigma_1 > \sigma_2 > \sigma_3 \) over time, which can lead to stress redistribution in the reservoir and caprock when gas is injected into the reservoir. The pore pressure of rock will increase, and the effective stress will decrease. Once the rock is subject to tensile or shear failure, the integrity of caprock for the gas storage will be damaged, and the gas leakage accident will occur. Most of the current studies on the mechanical integrity of caprock for underground gas storage have been based on conventional triaxial compression tests. However, due to the presence of tectonic stresses, the stress state of subsurface rock is 3D anistorpic geostress state. These studies ignore the effect of intermediate principal stresses on the mechanical behaviour of the rock, which will cause the results not being consistent with reality. Therefore, it is crucial to study the integrity of the caprock under 3D anistorpic geostresses.

In the study of the mechanical properties of rock under 3D anistorpic geostress, Minaeian et al. investigated the effects of different saturations of water and axial stress differences (the difference between the intermediate principal stress and the minimum principal stress) on shale deformation and strength. It was found that the peak strength of the shale increases at low and medium stress differences, while it decreases at high stress differences. Feng et al. conducted a series of true triaxial compression tests on mudstone and granite specimens. They found the hard rock strength was characterized by asymmetric variation with intermediate principal stress. Ma et al. analyzed the effect of intermediate principal stresses on the damage characteristics of rocks under different stress paths by true triaxial compression tests. Haimson and Chang found that the shear stress of the rock at peak damage showed a power exponential relationship with the mean positive stress, but this result could not describe the difference in deformation and strength of the rock at compression damage versus tensile damage. Deng et al. investigated the effect of
intermediate principal stress on the failure behavior of rocks and found that the peak failure strength of rocks reached a maximum when the intermediate principal stress coefficient is approximately equal to 0.5. Song et al.\(^{13}\) divided the change process of tangential deformation modulus of mudstone during 3D anisotropic geostress loading into three stages: increasing stage, initial decreasing stage and rapid decreasing stage. It was observed that the shear stress at the failure surface was higher with the increase of the intermediate principal stress. To predict crack damage stresses, Gao et al.\(^{14}\) proposed two empirical models with large linear regression coefficients based on the intermediate and the minimum principal stress. The proposed models demonstrate that the crack damage stress shows an increasing trend with the increase of the intermediate and the minimum principal stress.

The constitutive model reflects the stress-strain relationship of the rock under the action of 3D anisotropic geostress. Lade and Duncan\(^{15}\) developed an elasto-plastic model using the non-associated flow law and plastic work as the hardening law based on the results of true triaxial compression tests. However, it did not take the body strain into account well, which may produce excessive shear expansion. Chen et al.\(^{16}\) proposed a unified constitutive model of rocks based on the newly modified generalized Zhang-Zhu criterion, which uses the uncorrelated plastic flow law and a potential function considering three effective principal stresses. Feng et al.\(^{17}\) developed a strain-softening elastic-plastic constitutive model of the rock based on the Mogi-Coulomb criterion and validated it in the finite-difference software FLAC\(^{3D}\). Li et al.\(^{18}\) developed an elastic-plastic damage constitutive model suitable for brittle rocks based on a modified nonlinear unified strength criterion. The model considered the effect of anisotropic damage and intermediate principal stresses. Huang et al.\(^{19}\) proposed a new nonlinear strength criterion for rock by combining the Hoek-Brown criterion and the nonlinear unified strength criterion.

Table 1 shows the potential functions, flow laws and hardening parameters of the rock constitutive models proposed by the above authors. The current constitutive models generally use the non-associated flow law and the isotropic hardening criterion. Since there are few yield criteria applicable to the 3D anisotropic geostress state, most scholars have obtained yield and potential functions for intermediate principal stresses by modifying the existing yield criteria. However, the potential functions obtained are limited in their applicability and do not accurately reflect the plastic flow direction of all rocks.
Table 1 Constitutive model of rocks under true three-dimensional stress state

<table>
<thead>
<tr>
<th>Potential function</th>
<th>Flow rule</th>
<th>Hardening parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>( G = \Phi ) ( G = t_{1}^{2} - k_{1} t_{3} )</td>
<td>Non-associated</td>
<td>( W )</td>
</tr>
<tr>
<td>Li et al. ( 15 )</td>
<td>( G = 4J_{1} \cos^{2} \phi_{n} - \frac{8 \sigma_{e}}{3} \cos \phi_{n} + \frac{\sqrt{2}}{3} \left( 19 \right) - 2m_{3} t_{3} )</td>
<td>Non-associated</td>
</tr>
<tr>
<td>Chen et al. ( 16 )</td>
<td>( G = \left[ \frac{q}{\sigma_{e}^{2}} + m_{3} \left( \frac{q}{\sigma_{e}} \right)^{2} \right] \left( t_{1}^{2} - 2m_{3} t_{3} \right) )</td>
<td>Non-associated</td>
</tr>
<tr>
<td>Huang et al. ( 19 )</td>
<td>( G = \frac{\sqrt{2}}{2} \left( \sigma_{1} - \sigma_{2} \right)^{2} + \frac{\sqrt{2}}{2} \left( \sigma_{2} - \sigma_{3} \right)^{2} - \frac{2 \sqrt{2}}{3} \sigma_{1} \cos \phi )</td>
<td>Associated</td>
</tr>
<tr>
<td>Feng et al. ( 17 )</td>
<td>( G = t_{1} - \frac{2 \sqrt{2}}{3} C \cos \phi - \frac{2 \sqrt{2}}{3} \sin \phi \sigma_{m,2} )</td>
<td>Non-associated</td>
</tr>
</tbody>
</table>

During the operation period of underground gas storage, a large amount of natural gas is injected into the geological storage, which generates pressure propagation and fluid transport in the reservoir and caprock. The stresses in the reservoir and caprock will be redistributed. The increase of pore pressure and the decrease of effective stress in the caprock are likely to cause the rupture and destabilization of the caprock, which will lead to the leakage of natural gas. Therefore, many scholars have studied the deformation and damage degree of caprock during gas injection in underground gas storage to evaluate the integrity of the caprock.\( 20-24 \)

Rutqvist et al. \( 25 \) used a conservative approach to calculate the probability of tensile failure to the caprock, where the caprock would fracture tenuously once the fluid pressure exceeded the minimum principal stress.

\[ P_{\kappa} = \sigma_{3} \]  

where \( \sigma_{3} \) is the minimum principle stress.

Rutqvist et al. \( 25 \) used the same conservative calculation method in their analysis of shear damage along existing fractures in the caprock, assuming that fractures can exist at any point in any direction. In this case, the Mohr-Coulomb damage criterion can be expressed as follows.

\[ |\tau| = \frac{1}{2} \left( \sigma_{m,2} - P_{\kappa} \right) \sin \phi + S_{0} \cos \phi \]  

where \( \tau \) is the shear stress, \( \sigma_{m,2} \) is the mean positive stress, \( S_{0} \) is the coefficient of cohesion, and \( \phi \) is the friction angle.
Liu et al.\textsuperscript{26} investigated the effects on formation displacement and caprock integrity during CO\textsubscript{2} injection in the Ordos Basin. The maximum pore pressure of the caprock layer must be less than the minimum principal stress of the caprock.

\[
\max p = \frac{\sigma_n}{n} \tag{3}
\]

where \( n \) is the safety factor, \( n = 1.25 \).

Liu et al.\textsuperscript{26} simultaneously determined the maximum injection pressure based on the Mohr-Coulomb shear damage criterion.

\[
\max p = p_r + \Delta p_r = p_r + \frac{UCS - \sigma_{rH} + N_a \times \sigma_{rV}}{\gamma - \alpha (1 - N_a)} \tag{4}
\]

where \( p_r \) is the initial reservoir pressure, \( \Delta p_r \) is the pore pressure variation values, \( \sigma_{rH} \) is the initial vertical effective stress, \( \sigma_{rV} \) is the initial horizontal effective stress.

Karimnezhad et al.\textsuperscript{27} established a 3D geomechanical finite element model to study the effect of CO\textsubscript{2} injection on the cap, in which the Mohr-Coulomb failure criterion was used to determine whether any potential shear failure of the rock had occurred. Vilarrasa et al.\textsuperscript{28} investigated the hydrodynamic response of CO\textsubscript{2} injection to a deep brine layer and used the Drucker-Prager damage criterion to calculate the likelihood of damage occurring in the cap rock. Xiao et al.\textsuperscript{29} developed a geomechanical model based on the coupling method to study the long-term coupled chemical-mechanical processes in the inhomogeneous caprock. The Mohr-Coulomb failure criterion was used to determine the failure state. Bakhtiari et al.\textsuperscript{30} used the Mohr-Coulomb failure criterion to calculate stability thresholds of rock in assessing the integrity of caprock for the Sarajeh oil field in Iran.

At present, the evaluation of caprock integrity for underground gas reservoirs is mostly based on the coupled geomechanical models. However, the constitutive model they adopt do not consider the effect of intermediate principal stress, such as Mohr-Coulomb and Hoek-Brown constitutive model, which cannot reflect real stress state of underground rock mass. These studies ignore the effect of intermediate principal stresses on the mechanical behaviour of the rock, which will cause the results not being consistent with reality. Therefore, it is crucial to study the integrity of the caprock under 3D anisotropic geostress.

In this paper, the siltstone of caprock for H underground gas storage in Xinjiang is selected as the research object. A series of true triaxial compression tests are carried out to study the mechanical
behavior of the rock. The Triple-Mean-Normal-Stress constitutive model (TMNS) is embedded into a FEM code to investigate the integrity of caprock for the storage. In order to evaluate the integrity of the caprock during the gas injection stage, the Mohr-Coulomb, Mogi-Coulomb and TMNS constitutive models were chosen to analyze the variation of pore pressure, stress and displacement. Finally, the ultimate upper limit pressure during gas injection in the reservoir is analyzed. The research will enrich the basic theory of rock constitutive model, and provide a theoretical basis for the research on the integrity of caprock for gas storage and the geological storage of CO₂.

2 Mechanical properties and constitutive model

2.1 Mechanical properties

The specimens were taken from the same section of core in the caprock (3500 m in depth) of H underground gas storage in Xinjiang, which was processed into rectangular specimens of 25 mm × 25 mm × 50 mm. The novel Mogi type of the true triaxial test system is used for testing, which is independently developed by Northeastern University. According to the actual effective stress at the core of the caprock, we set a series of true triaxial compression test. Additional details are presented by our previous study.

According to our previous study, we can see that the initiation stress, damage stress and peak strength of siltstone in a certain range become larger with the increase of intermediate principal stress under the action of 3D anisotropic geostress. The increase of both minimum and intermediate principal stresses increases the peak strength of the rock. When the intermediate principal stress and the minimum principal stress are equal, the intermediate principal strain curve coincides with the minimum principal strain curve. However, with the gradual increase of the intermediate principal stress, the intermediate principal strain curve gradually deviates from the minimum principal strain curve and becomes farther and farther apart, and the deformation of the rock mainly follows the direction of the minimum principal stress.

Under the condition of constant minimum principal stress, the peak strength of siltstone increases with the increase of intermediate principal stress in a certain range, and the intermediate principal stress plays a protective role for siltstone. However, the peak strength of the siltstone will gradually decrease when the intermediate principal stress is far greater than the minimum principal stress. The protective effect of the intermediate principal stress on the siltstone will turn
into the damage effect. Under this condition, the failure mode of rock is equivalent to tensile failure mode.  

2.2 Elastoplastic constitutive model

2.2.1 Elastic behavior

It is assumed that the siltstone is isotropic material and the elastic part of the rock follows the generalized Hooke’s law:

\[
\begin{bmatrix}
\Delta \varepsilon_x \\
\Delta \varepsilon_y \\
\Delta \varepsilon_z
\end{bmatrix} =
\begin{bmatrix}
\frac{1}{E} & -\nu & -\nu \\
-\nu & \frac{1}{E} & -\nu \\
-\nu & -\nu & \frac{1}{E}
\end{bmatrix}
\begin{bmatrix}
\Delta \sigma_x \\
\Delta \sigma_y \\
\Delta \sigma_z
\end{bmatrix}
\]  

where \( E \) represents the Young’s modulus, \( \nu \) represents the Poisson’s ratio, \( \Delta \sigma \) represents the stress increment, \( \Delta \varepsilon \) represents the strain increment.

2.2.2 Yielding behavior

Mogi-Coulomb yield criterion is modified to obtain a three-average normal stress yield function as shown in Eq. (6).

\[
F(\sigma) = \frac{1}{3} \sqrt{\frac{1}{3} \left( (\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2 \right)} - \frac{1}{2} \left( \frac{\sigma_1 + \sigma_2}{2} - b_2 \right) - \frac{1}{2} \left( \frac{\sigma_1 + \sigma_3}{2} - c_2 \right) - \frac{1}{2} \left( \frac{\sigma_2 + \sigma_3}{2} - d_2 \right) - a_2
\]  

where \( a_2, b_2, c_2, d_2 \) are the material parameters related to mechanical properties of rock.

2.2.3 Flow rule

Flow rule reflects flow direction of plastic deformation as shown in Eq. (7). The non-associated flow rule is adopted, and the expression of the potential function is shown in Eq. (8).

\[
d\varepsilon^p_{ij} = d\lambda \frac{\partial G(\sigma)}{\partial \sigma_{ij}}
\]  

where \( d\lambda \) represents the plastic factor, \( G(\sigma) \) represents the potential function.

\[
G(\sigma) = \frac{1}{3} \sqrt{\frac{1}{3} \left( (\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2 \right)} - \frac{1}{2} \left( \frac{\sigma_1 + \sigma_2}{2} - b_2 \right) - \frac{1}{2} \left( \frac{\sigma_1 + \sigma_3}{2} - c_2 \right) - \frac{1}{2} \left( \frac{\sigma_2 + \sigma_3}{2} - d_2 \right)
\]  

where \( b_2, c_2, d_2 \) are the material parameters related to mechanical properties of rock.

Fig. 1 is the comparison diagram of the potential function of TMNS model, Mohr-Coulomb model and Mogi-Coulomb model on the \( \pi \) plane. It can be seen from the figure that the potential function of TMNS model is a regular convex figure on the \( \pi \) plane. The potential function plane of
the Mogi-Coulomb model is inscribed in the potential function plane of TMNS model. The potential function plane of the Mogi-Coulomb model is concave on the negative axis, which is unstable for geotechnical materials in traditional plastic mechanics.

2.2.4 Hardening law

The isotropic hardening assumption is generally used in geotechnical static models. The hardening criterion determines the magnitude of the plastic strain increment caused by the increment of stress. The plastic deflection strain is used as the hardening parameter.

\[ d\varepsilon_p = \sqrt{\frac{(d\varepsilon_1 - d\varepsilon_2)^2 + (d\varepsilon_2 - d\varepsilon_3)^2 + (d\varepsilon_3 - d\varepsilon_1)^2}{2}} \]

(9)

where \( d\varepsilon_1, d\varepsilon_2, d\varepsilon_3 \) are the plastic strain increments in three principal stress directions.

The plastic deviatoric strain \( \varepsilon_q^p \) which is determined by its corresponding stress level is a function of deviatoric stress as shown in Eq. (10). Eq. (11) is a function of the plastic deviatoric strain and the deviatoric stress obtained by fitting curve.\(^{32}\) Three groups of coefficients \( m \) and \( n \) can be obtained by fitting the functional relationship between plastic deviatoric strain and deviatoric stress. The three groups of curves are close to each other, taking \( m = -4.46, \ n = -0.014. \)\(^{32}\)

\[ \varepsilon_q^p = \sqrt{\frac{(\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_2 - \varepsilon_3)^2 + (\varepsilon_3 - \varepsilon_1)^2}{2}} = f(\sqrt{J_2}) \]

(10)

where \( J_2 \) is the second invariant of stress deviation.

\[ \varepsilon_q^p = \sqrt{\frac{(\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_2 - \varepsilon_3)^2 + (\varepsilon_3 - \varepsilon_1)^2}{2}} = m \cdot (1 - e^{"\sqrt{\varepsilon_1}^2}) \]

(11)

2.3 Model validation

The numerical model with a size of 25 mm \( \times \) 25 mm \( \times \) 50 mm was established. The model mesh is divided into 250 elements using hexahedron structural elements and the global uniform step method. Table 2 shows the rock mechanical parameters of the siltstone, which can be found in our previous study.\(^{32}\) The true triaxial compression test is carried out in ABAQUS. The compiled TMSN constitutive model subroutine is called into ABAQUS software for calculation. Fig. 2 is the compile flow chart of user subroutine.
Table 2 Rock mechanics parameters for siltstone models

<table>
<thead>
<tr>
<th>$E$ (GPa)</th>
<th>$v$</th>
<th>$a_2$</th>
<th>$b_2$</th>
<th>$c_2$</th>
<th>$d_2$</th>
<th>$b_3$</th>
<th>$c_3$</th>
<th>$d_3$</th>
<th>$m$</th>
<th>$n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>22</td>
<td>0.13</td>
<td>-27.5</td>
<td>0.82</td>
<td>-0.26</td>
<td>0.49</td>
<td>0.49</td>
<td>-0.29</td>
<td>0.21</td>
<td>-4.46</td>
<td>-0.014</td>
</tr>
</tbody>
</table>

Fig. 3 shows the comparison of the pre-peak stress-strain curve between the numerical calculation results of TMSN model and the true triaxial compression test results of the siltstone. It can be seen that the TMSN model established in this paper can be well consistent with the pre-peak test results of the siltstone, which verifies the correctness of the TMSN model and the user subroutine compilation.

3 Simulation method

3.1 Geological model

H gas storage is located in the southern edge of the Junggar Basin and its overall structural form is an EW-trending anticline. Gas fields are mainly distributed in the strata of Paleogene Ziniquanzi Formation. According to the logging data, the parameters of each layer for the gas reservoir are shown in Table 3.

Table 3 Parameters of each layer for the gas reservoir

<table>
<thead>
<tr>
<th>layer</th>
<th>Thickness (m)</th>
<th>Average porosity (%)</th>
<th>Average permeability (mD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Caprock</td>
<td>150</td>
<td>3.9</td>
<td>0.021</td>
</tr>
<tr>
<td>Reservoir</td>
<td>120</td>
<td>19.1</td>
<td>34.9</td>
</tr>
<tr>
<td>Floor</td>
<td>150</td>
<td>3.6</td>
<td>0.012</td>
</tr>
</tbody>
</table>

As shown in Fig. 4, the numerical model with a size of 420 mm × 2000 mm × 2000 mm was established. The caprock, reservoir and floor are anticlinal structures. Equivalent load is applied to the stratum above the caprock, and the pore pressure gradient of the model is 10 kPa/m. For ease of analysis, only one injection well is set in the model with a well radius of 0.5 m, which is located in the middle of the model. The bottom of the well is located at the junction of reservoir and floor. In order to meet the requirements of fluid-solid coupling calculation, 8-node hexahedral elements and three-dimensional linear pore pressure (C3D8P) are used. There were 54080 elements being generated. In this model, a vertical monitoring line through the caprock, reservoir and floor of is set at a horizontal distance of 10 m from the injection well. Ten horizontal monitoring points are set at the intersection of the reservoir and the caprock. Each monitoring point is 100 m apart with the starting point at the injection well wall and the end point at the right boundary of the model.
The boundary conditions of the model are as follows:

Fixed vertical displacement at the bottom of the model and horizontal displacement at the left and right boundaries of the model. The top surface was allowed to deform freely. The bottom of the model is impermeable, and the front, rear, left and right parts of the model are fluid pressure boundary conditions, allowing fluid to enter and exit. Hydrostatic pressure is applied to the upper part of the model with the pore pressure gradient of 10 kPa/m.

3.2 Conditions and medium parameters

In order to correctly evaluate the integrity of caprock for underground gas storage, three conditions are set as shown in Table 4. In these three conditions, the Mohr-Coulomb, Mogi-Coulomb and TMNS constitutive model are used for caprock, respectively. The Mohr-Coulomb elastoplastic constitutive model is adopted for the constitutive model of the reservoir and floor for the H gas storage.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Injection rate (m³/s)</th>
<th>Injection time (day)</th>
<th>Storage time (day)</th>
<th>Production rate (m³/s)</th>
<th>Production time (day)</th>
<th>Constitutive model (Caprock)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.5</td>
<td>210</td>
<td>30</td>
<td>5.5</td>
<td>120</td>
<td>Mohr-Coulomb</td>
</tr>
<tr>
<td>2</td>
<td>4.5</td>
<td>210</td>
<td>30</td>
<td>5.5</td>
<td>120</td>
<td>Mogi-Coulomb</td>
</tr>
<tr>
<td>3</td>
<td>4.5</td>
<td>210</td>
<td>30</td>
<td>5.5</td>
<td>120</td>
<td>TMNS</td>
</tr>
</tbody>
</table>

The medium parameters of reservoir, caprock and floor refer to the geological data of H gas storage in other scholars' articles. Table 5 is the media parameters for reservoir, caprock and floor. The parameters of Mohr-Coulomb, Mogi-Coulomb and TMNS constitutive model are determined by stress-strain curve obtained from true triaxial compression test. Fig. 5 shows the fitting results of Mohr-Coulomb, Mogi-Coulomb and TMNS constitutive models and true triaxial compression test curves at a stress level of \( \sigma_1 = 45\text{MPa}, \sigma_2 = 80\text{MPa} \). Due to the time-hardening model adopted by Mohr-Coulomb model, the parameters of the hardening part are determined by the relationship between the cohesion and the equivalent plastic strain in ABAQUS.

The integrity of the specimens used in the true triaxial compression test is significantly better than the underground rock mass. Therefore, the deformation degree of rock in practical engineering is greater than that of rock in true triaxial compression test. According to the geological data, the Young’s modulus of the caprock for H gas reservoir is 8 GPa. However, the Young’s modulus of the Mohr-Coulomb constitutive model obtained by fitting is 22 GPa. In order to conform to the
actual project, we reduce the Young's modulus obtained by fitting to 8 GPa, and increase the elastic and plastic deformation of the stress-strain curve in an equal proportion. The parameters of constitutive model are obtained by fitting the Mogi-Coulomb and TMNS constitutive model with the adjusted stress-strain curve.

The parameters of constitutive model are as follows. TMNS model elastic parameter:
\[ E = 8 \text{ GPa}, \quad \nu = 0.13, \quad a = -27.5, \quad b = 0.82, \quad c = -0.26, \quad d = 0.49, \quad \text{plastic parameter:} \quad h = 0.49, \quad s = -0.29, \quad s = 0.21, \quad m = -1.34, \quad n = -0.014. \]
Mogi-Coulomb model elastic parameter: \[ E = 8 \text{ GPa}, \quad \nu = 0.13, \quad a = -31.46, \quad b = 0.79, \quad \text{plastic parameter:} \quad h = 0.78, \quad m = -1.34, \quad n = -0.014. \]
Mohr-Coulomb model parameter: \[ E = 8 \text{ GPa}, \quad \nu = 0.13, \quad \text{cc, the hardened part is determined by the relationship between cohesion and equivalent plastic strain in ABAQUS.} \]

### Table 5 Media parameters for reservoir, caprock and floor

<table>
<thead>
<tr>
<th>Stratum</th>
<th>Density (kg/m³)</th>
<th>Young’s modulus (GPa)</th>
<th>Poisson's ratio</th>
<th>Permeability (mD)</th>
<th>Porosity (%)</th>
<th>Friction angle (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Caprock</td>
<td>2600</td>
<td>8</td>
<td>0.13</td>
<td>0.021</td>
<td>3.9</td>
<td>30</td>
</tr>
<tr>
<td>Reservoir</td>
<td>2200</td>
<td>4</td>
<td>0.27</td>
<td>35.5</td>
<td>18.6</td>
<td>25</td>
</tr>
<tr>
<td>Floor</td>
<td>2300</td>
<td>5</td>
<td>0.20</td>
<td>0.012</td>
<td>3.6</td>
<td>25</td>
</tr>
</tbody>
</table>

### 4 Results

#### 4.1 Analysis of pore pressure field in gas storage

Fig. 6 shows the pore pressure distribution of the caprock, reservoir and floor on the vertical monitoring line at the end of the gas injection stage. It can be seen from Fig. 6 that the pore pressure of the caprock shows an increasing trend with the increase of depth, and reaches the maximum value at the interface between the caprock and the reservoir. The pore pressure of the reservoir first increases and then decreases with the increase of depth, and the maximum pore pressure is located in the center of the reservoir. The pore pressure of the floor decreases gradually with the increase of depth.

Fig. 7 shows the pore pressure distribution of reservoir-caprock interface at the end of gas injection stage. As can be seen from Fig. 7, the pore pressure of reservoir decreases gradually with the distance from monitoring point to well wall of gas injection well increasing. At the reservoir-caprock interface, the simulated pore pressure adopting Mohr-Coulomb model is the maximum and
that adopting TMNS model is the minimum.

Table 6 shows the pore pressure at the reservoir-caprock interface, the maximum pore pressure of reservoir and the pore pressure at the reservoir-floor interface under different conditions at the end of gas injection stage. It can be seen that the pore pressure adopting Mohr-Coulomb model is 3.01 MPa higher than that adopting TMNS model at the reservoir-caprock interface, and the maximum reservoir pressure adopting Mohr-Coulomb model is 0.60 MPa higher than that adopting TMNS model. In conclusion, during the gas injection stage of the numerical simulation, the pore pressure obtained by Mohr-Coulomb constitutive model is higher than that obtained by TMNS constitutive model at the reservoir-caprock interface.

Table 6 Pore pressure value of gas storage under different working conditions at the end of gas injection stage

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Reservoir-caprock pore pressure (MPa)</th>
<th>Maximum pore pressure of reservoir (MPa)</th>
<th>Reservoir-floor interface pore pressure (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>65.98</td>
<td>68.65</td>
<td>64.42</td>
</tr>
<tr>
<td>2</td>
<td>64.32</td>
<td>68.24</td>
<td>64.15</td>
</tr>
<tr>
<td>3</td>
<td>62.97</td>
<td>68.05</td>
<td>63.97</td>
</tr>
</tbody>
</table>

4.2 Analysis of stress field in gas storage

Fig. 8 shows the maximum principle stress distribution of the caprock, reservoir and floor on the vertical monitoring line at the end of the gas injection stage. It can be seen from Fig. 8 that the maximum principle stress of caprock decreases with the depth increasing, and reaches the minimum value at the reservoir-caprock interface. According to the effective stress principle, the total stress remains unchanged, the effective stress will decrease when the pore pressure increases. The maximum principal stress of the reservoir first increases with the increase of depth, and then decreases suddenly at the reservoir-floor interface. The maximum principle stress in the floor increases with the depth increasing.

Fig. 9 presents the distribution of the maximum principle stress of reservoir-caprock interface at the end of gas injection stage. The maximum principle stress increases gradually with the distance from monitoring point to wall of gas injection well increasing. At the reservoir-caprock interface, the maximum principle stress adopting Mohr-Coulomb model is the minimum and that adopting TMNS model is the maximum. The maximum principle stress obtained by Mohr-Coulomb constitutive model is lower than that obtained by TMNS constitutive model at the reservoir-caprock.
interface during the gas injection stage of numerical simulation.

4.3 Analysis of displacement field in gas storage

Fig. 10 shows displacement distribution of the caprock, reservoir and floor on the vertical monitoring line at the end of the gas injection stage. The displacement of gas storage strata increases with the decrease of depth. The displacement at the caprock adopting Mohr-Coulomb model is the maximum and that adopting TMNS model is the minimum. It demonstrates that when the Mohr-Coulomb constitutive model is selected for the caprock, it is more likely to cause engineering geological disasters. When the TMNS model is selected, the vertical displacement of the caprock is the minimum. Therefore, when the Mohr-Coulomb constitutive model is adopted for the gas storage caprock, the vertical displacement of the caprock will be relatively large, resulting in conservative upper limit pressure of the gas injection in the gas storage.

Fig. 11 presents the vertical displacement distribution of reservoir-caprock interface at the end of gas injection stage. It can be seen from Fig. 11 that with the increase of the distance from monitoring point to the wall of gas injection well, the vertical displacement of the reservoir-caprock interface gradually decreases. It reveals that the closer to the wall of the gas injection well, the greater the uplift displacement of the surface, and the rock around the gas injection well will be more vulnerable to damage. At the reservoir-caprock interface, the vertical displacement adopting Mohr-Coulomb model is 0.168 m and that adopting TMNS model is 0.147 m. The vertical displacement at the reservoir-caprock interface adopting Mohr-Coulomb model is 0.021 m higher than that adopting TMNS model.

5 Discussions

5.1 Integrity analysis of the caprock for gas storage

Fig. 12 shows the strain distribution of gas storage at the end of gas injection stage. It can be seen that the deformation degree of the reservoir rock mass of the gas storage is significantly higher than that of the caprock and the floor for the gas storage. The deformation of rock mass is mainly concentrated around the gas injection well, especially at the interface of reservoir and caprock, which indicates that the rock mass here is most vulnerable to damage. Therefore, the stress state of the rock at the reservoir-caprock interface around the gas injection well should be analyzed to study the integrity of the caprock.
The distribution of plastic zone of H gas storage at the end of gas injection stage is shown in Fig. 13. It can be seen that the plastic area of the gas storage in the gas injection stage is mainly distributed at the reservoir-caprock interface around the well wall. The plastic area obtained adopting Mohr-Coulomb model is the largest, and the plastic area obtained adopting TMNS model is the smallest. It is indicated that the integrity of gas reservoir caprock is more vulnerable to damage when Mohr-Coulomb constitutive model is adopted, which can’t consider the intermediate principal stress.

For underground gas storage, there are two main modes of rock failure at the reservoir-caprock interface around the gas injection well: tensile failure and shear failure. When the tensile stress of the rock exceeds the tensile strength of the rock itself, the rock will undergo tensile failure. According to the first strength theory of materials, it is known that Eq. (12) needs to be satisfied if the rock at the reservoir-cover intersection is to be protected from tensile damage.

\[ \sigma' \leq \sigma_t \]  

\[ \text{where } \sigma' \text{ is the minimum principal effective stress, } \sigma_t \text{ is the tensile strength of rock.} \]  

The rock at the reservoir-caprock interface of the underground gas reservoir are siltstone, which are sedimentary rocks with relatively low tensile strength. According to engineering experience, a tensile strength of 0 MPa for siltstone is generally taken as the standard in the reservoir cap integrity study.

\[ \sigma \leq 0 \]  

\[ \text{During gas injection, the effective stress of the rock gradually decreases as the pore pressure continues to increase. When the minimum principal effective stress of the rock decreases to 0 MPa, that is, when the pore pressure in the formation is equal to the initial minimum principal stress of the formation, damage to the rock occurs. The effective stress principle can be expressed as follows.} \]

\[ \sigma' = \sigma - \alpha \sigma_p \]  

\[ \text{where } \sigma' \text{ is the effective stress, } \sigma \text{ is the total stress, } \alpha \text{ is the effective stress coefficient, } \sigma_p \text{ is the pore pressure.} \]  

According to the effective stress principle, if natural gas is continuously injected during the gas injection stage, the pore pressure inside the reservoir will continue to increase. As the total stress in the reservoir remains constant, the minimum principal stress in the rock at the reservoir-cap
interface around the gas injection well wall will continuously decrease. As can be seen from Table 7, the minimum principal stresses at the reservoir-caprock intersection around the gas injection well wall simulated for Mohr-Coulomb and TMNS model are 6.86 MPa and 9.73 MPa, respectively. Therefore, the effective rock stress at the reservoir-caprock interface adopting Mohr-Coulomb model is the first to decrease to zero, resulting in tensile failure to the rock and damage to the integrity of the cover, while the rock at the reservoir-cover interface adopting TMNS model is relatively the least susceptible to tensile failure.

In this paper, the TMNS strength criterion considering the effect of intermediate principal stress is proposed.  

\[
r_{\sigma_{3}} = a_{i} + \frac{\sigma_{1} + \sigma_{3}}{2} b_{i} + \frac{\sigma_{1} + \sigma_{3}}{2} c_{i} + \frac{\sigma_{1} + \sigma_{3}}{2} d_{i} \tag{15}
\]

where \( a_{i}, b_{i}, c_{i}, d_{i} \) are the material parameters, \( a_{i} = 6.04, \ b_{i} = 0.13, \ c_{i} = 0.89, \ d_{i} = -1.38 \).

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Maximum principle stress (MPa)</th>
<th>Intermediate principal stress (MPa)</th>
<th>Minimum principle stress (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>45.89</td>
<td>19.36</td>
<td>6.86</td>
</tr>
<tr>
<td>2</td>
<td>47.42</td>
<td>20.25</td>
<td>8.52</td>
</tr>
<tr>
<td>3</td>
<td>48.59</td>
<td>21.18</td>
<td>9.73</td>
</tr>
</tbody>
</table>

Fig. 14 illustrates the Mohr-Coulomb, Mogi-Coulomb and TMNS model strength envelopes. To represent the effect of \( \sigma_{3} \), we draw the envelopes of the Mogi-Coulomb and TMNS models for the three cases \( \sigma_{2} = \sigma_{3}, \ \sigma_{2} = \frac{\sigma_{1} + \sigma_{3}}{2}, \ \sigma_{2} = \sigma_{1} \), respectively. It can be seen that with the increase of \( \sigma_{2} \), the slope of the Mogi-Coulomb strength envelope shows a trend of decreasing first and then increasing. When \( \sigma_{2} = \frac{\sigma_{1} + \sigma_{3}}{2} \), the slope of the strength envelope is the smallest, and when \( \sigma_{2} = \sigma_{3} \) or \( \sigma_{2} = \sigma_{1} \), the slope is the largest. The real Mogi-Coulomb strength envelope is in the above range and the form of the envelope will not necessarily be linear. It can also be seen that with the increase of \( \sigma_{2} \), the slope of the strength envelope of the TMNS model keeps decreasing. When \( \sigma_{2} = \sigma_{3} \), the slope of the strength envelope is the smallest, and when \( \sigma_{2} = \sigma_{1} \), the slope is the largest. The real TMNS strength envelope is in the above range and the form of the envelope will not necessarily be linear. As can be seen in Fig. 14, both TMNS and Mogi-Coulomb models have a portion of their envelopes located in the lower part of the envelope for the Mohr-Coulomb model.
which indicates that when $\sigma$ is less than a certain value, the Mogi-Coulomb and TMNS model will underestimate the shear strength of the rock. In the study of this paper, this value is around 45 MPa for Mogi-Coulomb and around 5 MPa for TMNS.

As can be seen in Fig. 14, the black, blue, red, and green Mohr circles represent the initial stress state of the caprock and the stress state of the caprock at the end of gas injection when the Mohr-Coulomb model, Mogi-Coulomb model, and TMNS model are selected for the caprock, respectively. During the gas injection phase, the pore pressure inside the reservoir will continue to increase as the gas continues to be injected. According to the effective stress principle, the total stress in the reservoir remains constant, thus the effective stress in the rock at the reservoir-cap interface around the gas injection well wall is constantly decreasing. The Mohr circle moves to the left along the X-axis.

In this study, as the gas continues to be injected, the rocks adopting Mohr-Coulomb model will be the most vulnerable to undergo shear failure and the integrity of the caprock will be the most vulnerable to be destroyed. The rocks adopting TMNS model will be the least vulnerable to undergo shear failure and the integrity of the cover will be the least vulnerable to be destroyed. From the strength envelope, all Mohr circles will first intersect with the Mogi-Coulomb envelope, then with the Mohr-Coulomb envelope, and finally with the TMNS envelope. It implies that the caprock adopting TMNS model and using TMNS damage criterion to determine if shear damage occurs in the rock will be not susceptible to be destroyed and the reservoir will receive a greater upper limit pressure.

5.2 Ultimate upper limit pressure of gas storage

The ultimate upper limit pressure is the maximum pressure during the operating cycle of the reservoir. Once the gas injection pressure exceeds the upper limit pressure, there is a possibility of tensile failure or shear failure at the reservoir reservoir-caprock interface. Therefore, the relationship between the 3D anistropic geostress state and the ultimate upper limit pressure at the reservoir reservoir-caprock interface during the gas injection cycle can be analyzed based on the hydraulic fracturing criterion, the Mogi-Coulomb intensity criterion and the effective stress principle. The upper limit pressure can be obtained from whether the rock at the reservoir-caprock interface undergoes tensile failure, which can be derived from Eqs. (12) and (13).
where $P'$ is the upper limit pressure.

The ultimate upper limit pressure of the gas reservoir can be obtained from whether the rock at the reservoir-caprock interface will undergo shear failure, which can be derived from the TMNS strength criterion and the effective stress principle.

The ultimate upper limit pressure at the reservoir-caprock interface can be derived from Eqs. (17) and (18).

The ultimate upper limit pressure at the interface of reservoir-caprock around gas injection wells, one is tensile failure and the other is shear failure. For tensile failure, tensile failure is considered to occur when the minimum principal effective stress in the rock is less than 0 MPa. For shear failure, damage is considered to have occurred when the stress state of the rock satisfies the TMNS strength criterion.

The stress state of the caprock of gas reservoir is as follows: minimum horizontal principal stress $\sigma_3 = 66$ MPa, vertical principal stress $\sigma_2 = 83$ MPa, maximum principal stress $\sigma_1 = 91$ MPa.

The effective stress coefficient of caprock rock is 0.6. The ultimate upper limit pressures for tensile and shear failure to the interface between reservoir and caprock are 110 MPa and 90.55 MPa, respectively, from Eqs. (16) and (19), indicating that the rock at the interface between the reservoir and caprock is more susceptible to shear failure. The ultimate upper limit pressure, calculated by the Mohr-Coulomb principal model, is 79.61 MPa. Comparing the upper limit pressure calculated by the Mohr-Coulomb and the TMNS model, it can be found that the TMNS model can effectively improve the upper limit pressure of the gas storage by 13.7% compared with the upper limit pressure calculated by the Mohr-Coulomb model.
7 Conclusions

This paper evaluates the integrity of the caprock during the gas injection stage. The Mohr-Coulomb, Mogi-Coulomb and TMNS principal constitutive models were chosen to analyze the variation of pore pressure, stress and displacement in the reservoir during the gas injection stage. Finally, the critical limit pressure during gas injection in the reservoir is analyzed.

The maximum pore pressure appears around the gas injection well, and the further away from the gas injection well, the lower the pore pressure. The rock at the reservoir-caprock interface is most vulnerable to damage. Compared with the Mohr-Coulomb model, the TMNS model, which considers the intermediate principal stress, predicts the lower pore pressure and displacement at the reservoir-caprock interface. The pore pressure and vertical displacement at the reservoir-caprock interface adopting Mohr-Coulomb model are 3.01 MPa and 0.021 m higher than those adopting TMNS model, respectively.

The integrity of the caprock was evaluated using tensile failure criteria and shear failure criteria. During gas injection, the rocks at the reservoir-caprock interface using the TMSN constitutive model were the least vulnerable to damage, whether calculated using the tensile damage criterion or the shear strength criterion. When the caprock adopts TMNS model and uses TMNS damage criterion to determine if shear damage occurs in the rock, the reservoir will receive a greater upper limit pressure.

When the Mohr-Coulomb constitutive model is used to simulate the reservoir injection, a conservative upper limit pressure is used to prevent the integrity of the reservoir from being damaged. In contrast, when the TMNS constitutive model with 3D anistropic geostress is used to simulate the reservoir injection, the ultimate upper limit pressure of the reservoir will be increased by 13.7%. It is of great significance for the increase of production and capacity of the reservoir as well as peak regulation.

Declaration of competing 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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