Gas leakage mechanism in bedded salt rock storage cavern considering damaged interface

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Abstract

During the long-time operation of salt rock storage cavern, between its formations, damaged interfaces induced by discontinuous creep deformations between adjacent layers will possibly lead to serious gas leakage. In this paper, damaged interfaces are considered as main potential leakage path: firstly in meso-level, gas flow rule along the interface is analyzed and the calculation of equivalent permeability is discussed. Then based on porous media seepage theory, gas leakage simulation model including salt rock, cavity interlayers and interface is built. With this strategy, it is possible to overcome the disadvantage of simulation burden with porous-fractured double medium. It also can provide the details of gas flowing along the damaged zones. Finally this proposal is applied to the salt cavern in Qianjian mines (East China). Under different operation pressures, gas distributions around two adjacent cavities are simulated; the evolvement of gas in the interlayers and salt rock is compared. From the results it is demonstrated that the domain of creep damage area has great influence on leakage range. And also the leakage in the interface will accelerate the development of leakage in salt rock. It is concluded that compared with observations, this new strategy provides closer answers. The simulation result proves its validity for the design and reasonable control of operating pressure and tightness evaluation of group bedded salt rock storage caverns.

1. Introduction

Because of salt rock’s low permeability and self-healing capacity, it is considered as suitable storage media for underground natural gas and oil. The sealability of salt rock is an extremely important safety indicator during the long time operation period. It is reported some disasters induced by damaged cavity that happened home and abroad. The leakage of gas will result in catastrophic influences on the environment and energy reserves.

Generally, it is noted that salt rock has extremely compact structure, low permeability and good ductility. Therefore pure salt mine is considered as an ideal selection for energy storage and high radiation disposal. However, most of Chinese salt mines have many thin interbeds. According to current literature [1–3], the existence of the interlayers has obviously adverse influence on the oil and gas storage operation. If energy storage cavities are built in this kind of formations, interface between different formations would be easily damaged by discontinuous creep deformations between salt rock and interbeds will lead to severe gas leakage during the long-time recycling operation [1]. Hence, it is considered that more attention should be paid to the integrity test and leakage stability evaluation in Chinese salt rock cavern construction.
At home and abroad, much work has been done in the domain of permeability fluctuation under high operation pressure, creep and damage characteristic of pure salt rock [2–5] and their coupling fluid-mechanical responses [5–9]. However, when it comes to impure salt rock cavity, the related research just started in recent years. Especially the research emphasized on the influence of interlayers on the safety of salt cavern needs much more attention [10–12].

It is noted that seepage mechanism of high pressure gas in the interbedded salt rock is extremely complicated. How to build appropriate infiltration model and corresponding numerical simulation strategies are the key issues during the assessment of potential salt rock storage cavity and possible leakage volume. In this paper, damaged interface is taken as focal point. In meso-level, the evolvement of microcracks and broken rock particles in the damaged zones is simulated. Through this process, gas flow law along the interfaces is analyzed and its equivalent permeability is given. After that, based on porous media seepage theory, gas leakage model considering wall salt rock, interlayers and interface is built. With this strategy, the simulation burden is much easier than porous-fractured double medium; and it also can provide the gas flow mechanism along the damaged zones, which means it will simulate the percolation process of gas flow in salt rock, interbeds and damaged zones with a better way. Finally, combined with the cavity in Qianjiang mines, the damaged creep simulation model is built. Especially, this calculation model will consider the wall rock damaged zones in reasonable details. Under different operation pressures, gas distributions of two adjacent cavities are demonstrated; the evolvement of gas in the interlayer and salt rock is compared.

2. Equivalent permeability of damaged zones

Damaged zones of surrounding rock are regarded as the most possible leakage path for the gas in storage cavity. Especially when shear failure occurs at the interface between interbed and salt rock, there will be obvious slippage here, which means a damaged zone consisting of microcracks and broken rock particles are coming into being. In this section, based on fluid mechanics equation, mesomechanics calculation model for the damaged areas, and its equivalent permeability is provided too [13].

2.1. Heading flow equation of gas in microcracks

Navier-Stokes equation is employed for the flow mechanism of gas in fractures. For the migration of viscous fluid, if its flow velocity is \( \mathbf{u} \), pressure is \( p \) and density is \( \rho \), according to the corresponding derivation (gravity is neglected), N-S equation for incompressible fluid is as follows:

\[
\rho \left( \frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla) \mathbf{u} \right) + \nabla p - \nabla \cdot \left[ \mu \left( \nabla \mathbf{u} + \nabla \mathbf{u}^T \right) \right] = 0 \tag{1}
\]

\[
\nabla \cdot \mathbf{u} = 0 \tag{2}
\]
2.2. Calculation of equivalent permeability on meso-level

The schematic of calculation model of damaged zones considering mesomechanics is illustrated as Fig. 1. In this figure, connected region represents fractures, and regular quadrilateral is broken rock particles. It is assumed that all fractures are distributed in horizontal and vertical directions. During the calculation, the left side is considered as inlet, while as right side is outlet boundary: on the two side walls, their pressure is given equally, which equals to total pressure difference is broken rock particles. It is assumed that all fractures are connected region represents fractures, and regular quadrilateral is turbulent correction coefficient. The gas outlet velocity \( u \) at right boundary is integrated vertically, which equals to total fluid flow \( (Q) \) through this model. It is assumed that model length is \( l \) and width is \( a \) and horizontal pressure difference is \( \Delta P \), therefore on the basis of Darcy law, fluid flow will be calculated from sectional area \( (A) \) and pressure gradient.

\[
Q = k a \frac{\Delta P}{l} = k a l \frac{\Delta P}{T} = k a \Delta P
\]  

Equation (3) can be converted into another transformation as Equation (4). Here, \( k \) is equivalent permeability of fracture system. Its relationship with porous medium coefficient \( (K) \) is given by Equation (5): here \( \mu \) means gas dynamic viscosity and \( g \) is gravity.

\[
k = \frac{Q}{a \Delta P}
\]

\[
K = \frac{k \mu}{\rho g}
\]

Substituting Equation (4) into Equation (5), equivalent permeability of this model will be given with Equation (6):

\[
K = \frac{Q}{a \rho \Delta P}
\]

Table 1 illustrates the relationship between equivalent permeability and fracture width when porosity is considered. Fixed as 0.36. From the results, it is found that due to exist of micro-crack, equivalent permeability might increase a few order of magnitude.

3. Seepage theory of gas in surrounding rock

Both salt rock and interlayer are considered as homogeneous porous medium. For the damaged zones, its permeability is calculated with Equation (6). Therefore all formations will meet the requirements of porous seepage theory [14]. This theory is mainly based on idea gas state equation, equation of continuity, momentum equation and energy equation. In our application, the gas temperature \( (T) \) is regarded as constant; hence, energy equation is neglected. The idea gas state equation is Equation (7):

\[
p = \frac{RT}{M} \rho
\]

Here, \( M \) is gas molecular weight; gas constant: \( R = 8314 \text{ m}^2 \text{Pa} \text{s}^{-2} \text{K} \). For real gas, a correction factor \( Z \) (deviation factor compression factor) can be introduced as Equation (8):

\[
\frac{p}{\rho} = \frac{RTZ}{M}
\]

Basically gas velocity in the surrounding is slow; therefore the flow is simplified as laminar flow. For passive transient seepage, its equation of continuity is as Equation (9):

\[
\frac{\partial (\phi \rho)}{\partial t} - \nabla \cdot \left( \frac{K}{\mu} \nabla p \right)
\]

Here, \( \phi \) represents porosity and \( \delta \) is turbulent correction coefficient. Substituting Equation (8) into Equation (9), considering constant temperature, the partial differential equation for isothermal gas seepage is as Equation (10):

\[
\nabla \cdot \left( \frac{K}{\mu} \nabla p \right) = \frac{\partial}{\partial t} \left( \phi \rho \right)
\]

4. Simulation of gas leakage of bedded salt rock in Qianjiang and result discussions

The potential salt rock cavern located at Wang58 Mining of Jianghan Oilfield in Qianjiang City is chosen for the gas leakage simulation. According to local geological conditions and drilling data, the storage cavity is determined at depth from 1946 m (roof) to 2042 m (floor). So the Rock-salt cavity height is 96 m. Considering the convenience of cavity dissolving and its stability, cavern shape is finally set as a combination of upper half ellipse and lower half semicircle as illustrated in Fig. 3.

The simulation model is located at depth from 1920 m to 2080 m. Above the cavity, a mudstone interlayer is included with

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**Table 1**: Equivalent permeability VS fracture width.

<table>
<thead>
<tr>
<th>Fracture width/( \mu \text{m} )</th>
<th>Porosity</th>
<th>Equivalent permeability/( m^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.36</td>
<td>1.80209 ( \times 10^{-12} )</td>
</tr>
<tr>
<td>2</td>
<td>0.36</td>
<td>4.50522 ( \times 10^{-11} )</td>
</tr>
<tr>
<td>3</td>
<td>0.36</td>
<td>1.90112 ( \times 10^{-10} )</td>
</tr>
<tr>
<td>4</td>
<td>0.36</td>
<td>4.05470 ( \times 10^{-10} )</td>
</tr>
<tr>
<td>5</td>
<td>0.36</td>
<td>8.00082 ( \times 10^{-10} )</td>
</tr>
</tbody>
</table>

**Table 2**: Model creep and elastic—plastic parameters.

<table>
<thead>
<tr>
<th>Rock</th>
<th>E/GPa</th>
<th>( \nu )</th>
<th>C/MPa</th>
<th>( \phi )</th>
<th>A</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Salt rock</td>
<td>5.0</td>
<td>0.37</td>
<td>1.8</td>
<td>41</td>
<td>2 \times 10^{-6}</td>
<td>3.5</td>
</tr>
<tr>
<td>Interbed</td>
<td>6.0</td>
<td>0.29</td>
<td>1.9</td>
<td>35</td>
<td>3 \times 10^{-7}</td>
<td>1.5</td>
</tr>
</tbody>
</table>

\[ K = \frac{Q \mu}{a \rho g \Delta P} \]  

In Fig. 2, it is illustrated that the gas velocity contours with 50 \( \mu \text{m} \) crack width and porosity of 0.19. Table 1 illustrates the relationship between equivalent permeability and fracture width when porosity is fixed as 0.36. From the results, it is found that due to exist of micro-crack, equivalent permeability might increase a few order of magnitude.

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**Fig. 3**: Three-dimensional calculation model.
depth from 1925.5 m to 1934 m. Meanwhile, three mudstone interlayers that transverse the two cavities are located at 1953.7–1958 m, 1974.5–1978.5 m, and 2000.5–2004.5 m respectively. Besides, there is another interlayer located below the cavity (2044.5–2047.7 m).

According to literature [15,16], for the adjacent cavities, its central distance should be more than maximum cavity diameter. Therefore, here the central distance of two cavities is set as 300 m, and the corresponding mutual effect will be simulated too.

Table 3
Permeabilities of all formations.

<table>
<thead>
<tr>
<th></th>
<th>Salt rock</th>
<th>Interlayer</th>
<th>Interface</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Intact</td>
<td>Damaged</td>
<td>Intact</td>
</tr>
<tr>
<td>Permeability/m²</td>
<td>$1 \times 10^{-20}$</td>
<td>$1 \times 10^{-16}$</td>
<td>$1 \times 10^{-19}$</td>
</tr>
<tr>
<td>Porosity</td>
<td>0.01</td>
<td>0.1</td>
<td>0.03</td>
</tr>
<tr>
<td>Fracture width (m)</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
</tbody>
</table>
4.1. Creep damage calculation of surrounding rock

Firstly, creep analysis and storage cavern stability are conducted during its long-time operation. In Fig. 3 the creep calculation model is given.

The creep power function index model in FLAC3D is adopted here. According to laboratory experiments [16,17], model parameters are listed as Table 2.

Figs. 4 and 5 provides plastic zones and deformations of the model respectively. From Fig. 4, it is obvious that most

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Fig. 6. Pressure distribution of different operation pressures (10 years): (a) 11 MPa, (b) 15 MPa, (c) 17 MPa, (d) 20 MPa.
of plastic zones are located at the interfaces. In Fig. 5 it is found that maximum deformation happens at the middle part; the top deformation is obviously smaller than the middle. It is also concluded that interlayers has apparent inhibiting effect on cavity deformation: it is smaller than that in salt rock.

4.2. Simulation of gas migration

Substituting results from above creep simulation into gas seepage analysis, gas migration in surrounding rock can be depicted clearly. It is assumed that there is damaged zone at the upper interface of interlayer and salt rock, and its length is 10 μm. Based on the calculation method above, its equivalent
permeability is $10^{-14}$ m$^2$. Permeabilities of salt rock, interlayers, intact and damaged interface are listed in Table 3. Gas viscosity coefficient is $1.81 \times 10^{-5}$ Pa s.

In Fig. 6, the pore pressure distributions of surrounding rock considering two adjacent cavities are illustrated under different operation pressures. From figures, it is found that generally permeability of damaged interfaces increase quickly because of micro-crack, and gas migration also moves faster. Pore pressure along this path is much bigger than in salt rock, which means damaged interface becomes the main leakage path. Comparing the four figures, it is also found that smallest operation pressure (11 MPa) is inducing biggest damaged zones and maximum gas leakage. From Fig. 6(a), it is obvious that after 10 years’ runtime, the leakage path of two adjacent cavities are connected, which has adverse influence on safe performance of salt rock cavern. With the increasing of operation pressure, cavity stability is increasing too. In Fig. 6(d), mutual influence of two cavities is considered as neglectable.

When operation pressure is fixed at 17 MPa, gas pressure distributions in salt rock layer (depth is 1962 m) after 1 year, 3 years, 5 years and 10 years are illustrated in Fig. 7. Fig. 8 provides the same gas distribution along the 2nd interface of middle interlayer. From two figures, it is demonstrated that gas migration in salt rock is relatively small: after 10 years, the influenced area that has pressure over 2 MPa is less than 30 m. However, in the damaged interface, influenced length reaches 32 m, 53 m, 64 m and 100 m after 1 year, 3 years, 5 years and 10 years respectively.

5. Conclusions

Interlayers in salt rock can be a big factor in gas leakage assessment. In this paper, creep damage and its contribution to gas migration of an imbedded salt cavern are analyzed during the longtime operation, and several conclusions are demonstrated:

1) Once creep damage appears in the surrounding rock, it obviously increased rock permeability. Especially in the damaged interface, equivalent permeability is augmented with a few orders of magnitude, which became the main gas leakage path. Besides, there was remarkable gas pressure increase in these damaged zones.

2) It is found if operation pressure was kept low in a long time, creep damage expanded much more quickly. As a result, gas leakage and its migration range increased. In the worst case, a total leakage path along the interlayer interface will come into being in the adjacent caverns, which is a big threat to cavern operation. Therefore, a relatively high operation pressure is helpful for reducing damaged zones and gas leakage.

As can be seen, the strategy adopted in this paper has proven its validity for the cavity design of interbedded salt rock, and it provides reasonable control of operating pressure and tightness evaluation of group bedded salt rock storage caverns.

Acknowledgments

We acknowledge the following funds to give financial supports. They are China National Program on National natural sciences foundation of China Grant no.51104108 and 41172284, Key Basic Research Project (973 Program) Grant no. 2009CB724603.

References