Article

Tightness Analysis of Anhydrite Mine-Out Used for Underground Crude Oil Storage Considering Seepage–Stress Coupling: A Case Study

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Abstract: Good tightness is one of the necessary conditions for an anhydrite mine-out space to be used for underground crude oil storage. Combining engineering geological surveys, laboratory tests, and numerical simulations, this paper quantitatively analyses the tightness of the Anhui Hengtai anhydrite mine-out under different working conditions and discusses its suitability for underground crude oil storage. Triaxial compression tests of anhydrite rock considering seepage were carried out to study its hydraulic and mechanical characteristics during failure. The permeability coefficient–strain empirical formula of anhydrite was constructed. A numerical simulation was carried out on the basis of the finite difference method to study the tightness of the rock surrounding the mine-out after excavation and under 0.2 MPa, 0.6 MPa, and 1.0 MPa storage pressures, respectively. The results showed that the permeability coefficient increased with increasing storage pressure, and the growth rate gradually slowed after the storage pressure reached a certain value. Overall, the mine-out had good tightness, and the permeability coefficient of the surrounding rock was small. This study demonstrated the feasibility of using the anhydrite mine-out for crude oil storage and provides a scientific basis for the site selection of underground crude oil storage.

Keywords: anhydrite mine-out; underground crude oil storage; permeability evolution; permeability coefficient–strain empirical formula; tightness of crude oil storage

1. Introduction

Compared with traditional crude oil storage methods, including earth surface steel crude oil storage tanks, underground water-sealed crude oil storage caverns, and underground salt caves for crude oil storage, using underground abandoned anhydrite mine-out spaces to store crude oil has the advantages of shorter construction periods, lower investment costs, and broader application prospects [1–6]. As a type of underground storage, the storage of crude oil in anhydrite mine-out spaces should meet the following three conditions: the surrounding rock must have long-term stability during storage; the stored crude oil and oil gas must not leak out of the storage; and the stored crude oil must not interact with anhydrite rock [7].

The idea of using abandoned anhydrite mine-out to store crude oil was first put forward by Peng et al. (2013), who preliminarily analysed the feasibility of using the Anhui Hengtai anhydrite mine-out in China for crude oil storage and considered it to have the basic conditions for the construction of an underground crude oil storage facility [8]. Subsequently, some Chinese scholars took the Anhui Hengtai anhydrite mine-out as a case study and carried out systematic research on the scientific problems existing in the field.
of crude oil storage in anhydrite mine-out spaces. Previous research has shown that the Anhui Hengtai anhydrite mine-out has excellent airtightness and long-term stability for crude oil storage [4,7,9–11]. Anhydrite rock has no effect on the physical and chemical properties of crude oil, and the influence of crude oil on its mechanical properties can be ignored [7,12,13]. However, the current research on the tightness of anhydrite mine-out spaces used for underground crude oil storage is still limited. The permeability characteristics of the rock surrounding the anhydrite mine-out need to be further studied.

As a surrounding rock material, anhydrite is a dense sedimentary rock with extremely low porosity and permeability, which makes it impermeable in the intact state [14,15]. However, microcracks caused by the mining excavation and the loading of crude oil for storage may greatly increase the permeability of the disturbed surrounding rock, thus increasing the risk of crude oil leaking out of the storage through the surrounding rock [16–19]. In recent years, many scholars have carried out experimental research on the evolution law of rock permeability during deformation damage under hydro-mechanical coupling conditions, and their research shows that there is a certain relationship among stress, strain, and permeability throughout the process of rock damage failure. Moreover, the permeability curves show phase properties in the stress–strain process [20–33]. However, their research mainly focused on sandstone, limestone, granite, altered rock and other rock types, and there has been almost no research on anhydrite. Therefore, the absence of previous research and the proposal of using anhydrite mine-out space for crude oil storage stimulates the study of the permeability characteristics of the surrounding rock and the evaluation of its tightness. Some scholars found that the permeability coefficient of the surrounding rock of the underground water-sealed crude oil storage caverns after grouting can be reduced to a magnitude of $1 \times 10^{-7}$–$1 \times 10^{-9}$ m/s by comparing the numerical calculation results with the field monitoring data [34–36]. To reach the range of water inflow required by the specification, the permeability coefficient of the surrounding rock needs to reach a magnitude of $1 \times 10^{-9}$ m/s [37–39]. This can provide a reference for the tightness analysis of anhydrite mine-out used for underground crude oil storage.

In this paper, taking the Anhui Hengtai anhydrite mine-out as an engineering case study, a systematic method was proposed to analyse its tightness using triaxial compression tests while considering seepage and the results of the numerical simulation of strain. The stress–strain curve and permeability curve of anhydrite samples were obtained by using an MTS815 rock mechanics test system to construct the permeability coefficient–strain empirical formula. On the basis of numerical simulations, the unit strain information of anhydrite formation was collected, and the permeability coefficient of anhydrite formation was calculated by an empirical formula and visualized using FLAC3D version 5.0 software. The method of constructing the empirical formula of the permeability coefficient–strain of anhydrite rock and evaluating the tightness of the anhydrite mine-out used in this paper can be used as a reference for the analysis of permeability characteristics of other underground storage facilities.

2. Study Area

2.1. Engineering Overview

The Anhui Hengtai anhydrite mine-out is located in Ma’anshan City, Anhui Province, China. It began operation in 2004 with an ore production capacity of about $3 \times 10^5$ m$^3$/year [11]. After nearly 20 years of mining, a large underground mine-out space with a buried depth of more than 400 m and a volume of greater than $2.5 \times 10^6$ m$^3$ has been formed, including more than 350 transportation tunnels and mining caverns. Each transportation tunnel is 4.2 m high and 3.6 m wide; each mining cavern is 13 m high and 10 m wide; and the ore pillars are 10 m thick [7].
2.2. Geology and Hydrogeology

According to the geotechnical exploration reports, there are six main layers of strata in the mining area; from top to bottom, they are (1) the Quaternary (Q) alluvium and diluvium layer; (2) the upper Cretaceous (Ks) glutenite layer; (3) the Yueshan Formation (T2y) and Tongtoujian Formation (T2) silty fine sandstone layer; (4) the Dongmaanshan Formation (T2d) karst limestone layer; (5) the Dongmaanshan Formation (T2a) anhydrite layer; and (6) the Dongmaanshan Formation (T2a) dolomitic limestone layer, as shown in Figure 1.

There are three main gentle folds in the study area, with small dip angles that are between 10° and 35°. Small faults are developed inside the ore body, whose dip angles vary greatly. Seven main faults are distributed in the mine area, which can be roughly divided into the following two groups: one fault group trends in the NE direction; the other fault group is oblique and trends in the NW direction. The mining area is located in the fault depression zone formed by four faults cutting the anhydrite ore body [4]. The fissures in the ore body are undeveloped, with a small number of compressive joints, whose openness is small. There are almost no tensile fractures or obvious dominant joint directions.

![Figure 1. Mine-out area landform and geological structure [11].](image)

The groundwater in the mining area is mainly karst water, bedrock fissure water, and Quaternary pore water. The karst water mainly occurs in the karst limestone section of the Dongmaanshan Formation. This stratum has developed fissures and many karst caves. It is a strong aquifer and the direct water filling layer at the top of the anhydrite layer; the fissure water occurs in the local fracture development section of the upper Cretaceous (Ks) glutenite; the pore water occurs in Quaternary (Q) alluvium and diluvium, which is greatly affected by the weather. The anhydrite layer has no water and is very dense and thick. During anhydrite mining, there was no water seepage into the tunnel walls [11]. Overall, the anhydrite layer is a natural water-resisting layer.

3. Experimental Study

3.1. Sample Type

A group of cylindrical anhydrite samples with diameters of 50 mm and heights of 100 mm were prepared from an intact representative anhydrite rock with a relatively complete structure and no surface macroracks. According to the standard for Test Methods of Engineering Rock Mass (GB/T50266-2013), the diameter measurement deviations of the samples along the whole height were less than ±0.3 mm; the unevenness deviations at both ends of the samples were less than ±0.02 mm; the two ends of the samples were per-
pendicular to the axis; and their deviations were less than 0.25°. The samples were immersed in deionized distilled water under vacuum for at least 24 h to ensure saturation before testing.

3.2. Triaxial Compressive Strength of Anhydrite Samples

According to the relevant design of the axial load control mode in the test scheme, it is necessary to estimate the triaxial compressive strength of anhydrite under different confining pressures, and the corresponding calculation is completed using the Hoek–Brown failure criterion applicable to complete anhydrite, as shown in Equation (1) [4]:

\[
\sigma_1 = \sigma_3 + \sigma_c \left( \frac{m_1 \sigma_3}{\sigma_c} + 1 \right)^{0.5} \sigma_c = 68.48; m_1 = 18.35; R^2 = 0.8932
\]

where \(\sigma_1\) and \(\sigma_3\) are the major and minor principal stresses (MPa), respectively; \(\sigma_c\) is the uniaxial compressive strength (UCS) of the rock (MPa); and \(m_1\) is the Hoek–Brown failure criterion material constant derived from the triaxial testing of the intact rock.

3.3. Experimental Instrument and Schemes

Triaxial compression tests were conducted on the MTS815 rock mechanics test system. The equipment is a multifunctional electrohydraulic servo control rigid testing machine specially produced by the MTS company of the United States for rock and concrete tests. It has four independent closed-loop servos controlling the axial pressure, confining pressure, pore water pressure, and temperature. It is mainly used for various static and dynamic tests of rock and concrete materials, including uniaxial compression tests, uniaxial tensile tests, and triaxial confining pressure tests. The test system shown in Figure 2 is mainly composed of a loading system, controllers, and a measuring system. The loading system includes a hydraulic source, loading frame, actuator, servo valves, triaxial test system, pore water pressure test system, and temperature control system. The stiffness of the equipment’s loading frame is \(10.5 \times 10^3\) N/m, the maximum axial load can reach 4600 kN, the maximum axial tension can reach 2300 kN, and the maximum confining pressure and the maximum pore water pressure are both 140 MPa.

Figure 2. MTS815 rock mechanics testing machine.
In the triaxial compression tests, the permeability of the samples was obtained by the pressure pulse transient method. During the tests, the initial differential pressure at both ends of the samples was set to 1 MPa, i.e., \((P_{10} - P_{20})\) was 1 MPa. Considering that the in situ stress at the mining caverns of the Anhui Hengtai anhydrite mine-out is approximately 10 MPa and that stress concentration may occur at local positions during mining and crude oil storage, the target values of the confining pressure \(\sigma_3\) were set to 10 MPa, 15 MPa, and 20 MPa, and the loading speed was 0.05 MPa per second, referring to the standard (GB/T 50266-2013). After the confining pressure \(\sigma_3\) reached the target value, the confining pressure \(\sigma_3\) was held unchanged; the axial pressure \(\sigma_1\) was applied at up to 0.8 times the triaxial compressive strength at a loading rate of 1.00 MPa per second; and then the axial pressure \(\sigma_1\) was increased by controlling the displacement at a loading rate of 0.01 mm/min until the sample was damaged [40]. In the above process, multiple measuring points were used to measure the water pressures at both ends of the samples, which were recorded as \(P_{1f}\) and \(P_{2f}\) at time \(t_f\). The permeability and permeability coefficient of each measuring point in the test can be calculated by Equations (2) and (3):

\[
k_d = \frac{c_fBH\mu}{2\Delta t_f} \ln \frac{\xi_0}{\xi_f} = \frac{c_fBH\mu}{2\Delta t_f} \ln \frac{P_{20} - P_{2f}}{P_{1f} - P_{2f}}
\]

(2)

where \(k_d\) is the permeability of the sample \((m^2)\); \(c_f\) is the liquid compressibility coefficient; the empirical value of 0.0485 \((m^2/N)\) is taken; \(B\) is the volume of the containers at both ends of the sample \((m^3)\); \(H\) is the height of the sample \((m)\); \(\mu\) is the liquid dynamic viscosity \((Pa \cdot s)\); \(A\) is the cross-sectional area of the sample \((m^2)\); \(t_f\) is the cumulative time of data acquisition; \(\xi_0\) and \(\xi_f\) are the pore water pressure gradients of the samples at the beginning \((0)\) and end \((f)\) of the measurement, respectively \((Pa/m)\); and \(P_{10}, P_{20}, P_{1f},\) and \(P_{2f}\) are the water pressures at both ends of the sample at the beginning \((0)\) and end \((f)\) of the measurement, respectively \((Pa)\):

\[
k = \frac{k_d g}{\mu}
\]

(3)

where \(k\) is the permeability coefficient \((m/s)\) and \(g\) is the gravitational acceleration \((m/s^2)\).

3.4. Experimental Results

3.4.1. Evolution Characteristics of the Strength, Deformation; and Permeability

The experimental results showed that the stress–strain curves of the anhydrite samples were consistent with the conventional rock stress–strain curve, which can be divided into five stages: the pore compaction stage (I); the linear elastic deformation stage (II); the stable microcrack development stage (III); the unstable development stage (IV); and the post-failure stage (V). In Figure 3, the stress–strain curves and the permeability coefficient–strain curves are summarized and compared. \(\sigma_{ct}, \sigma_{ci}, \sigma_{cb},\) and \(\sigma_c\) correspond to the crack closure threshold, the crack initiation threshold, the crack damage threshold, and the peak strength, respectively [41–45]. The short platforms on the stress–strain curves are consistent with the measuring points selected during the permeability measurements. They were caused by the slight creep phenomenon influenced by the constant axial load during measurement, which had little impact on the experimental results. According to the curves, the existence of the confining pressure improved the peak strength of the samples and caused the samples to transition from brittle failure to plastic flow. Under a confining pressure of 20 MPa, the sample could still bear the maximum bearing capacity for a long time after reaching the peak strength, showing good ductility.
Figure 3. Stress–strain curves and permeability coefficient–strain curves for anhydrite rock under different confining pressures.
Existing research has shown that the pore compression in the initial stage of the triaxial compression test reduces the permeability coefficient [20–33]. Through the comprehensive analysis of the stress–strain curves and permeability coefficient–strain curves, the permeability coefficient changes of the anhydrite rock can be divided into four stages: the pore compaction and linear elastic deformation stage (I and II); the microcrack stable development stage (III); the unstable development stage (IV); and the post-failure stage (V). It can be concluded that with an increasing axial load, the permeability coefficient of anhydrite rock generally decreases first and then increases. The existence of confining pressure also affects the permeability coefficient of the anhydrite rock. The variation range of the permeability coefficient decreases with increasing confining pressure. Under a confining pressure of 20 MPa, the permeability coefficient changed very little overall. In addition, the initial permeability coefficient of the sample under 15 MPa confining pressure was abnormally high, and the decrease range of the permeability coefficient in the stage of pore compaction and linear elastic deformation was also abnormally large, indicating that there were defects in the internal structure of the sample.

3.4.2. Empirical Formula of the Permeability Coefficient–Strain

Table 1 shows the calculation results of the permeability coefficients of the samples under different confining pressures. On the basis of the permeability coefficient–strain curves of anhydrite samples under different confining pressures, and considering the influence of test errors, it is believed that the permeability coefficient does not change significantly and that it is approximately 0 before and after failure when the confining pressure is greater than 15 MPa. Considering the abnormal performance of the anhydrite sample at 15 MPa confining pressure, it is proposed to construct the empirical formula of the permeability coefficient and strain based on the permeability coefficient–strain curve of the anhydrite sample at 10 MPa confining pressure. Referring to the research results of Xiao et al. (2020) on the permeability characteristics of red sandstone, the empirical relationship between the permeability coefficient and strain of anhydrite at 10 MPa confining pressure was constructed using Equation (4), and the fitting results are shown in Figure 4 [25].

$$k = \begin{cases} \alpha |\varepsilon - \varepsilon_{kmin}|^{\beta} + k_0, & 0 \leq \sigma_3 \leq 15 \text{MPa} \\ 0, & \sigma_3 > 15 \text{MPa} \end{cases}$$  \quad (4)$$

where $\varepsilon$ is the axial strain (%); $\alpha$ and $\beta$ are the correlation coefficients, $\alpha = 0.80$, $\beta = 7.57$; $k_0$ is the initial permeability coefficient of the sample, $k_0 = 4.00 \times 10^{-11}$ m/s; and $\varepsilon_{kmin}$ is the axial strain corresponding to the minimum permeability coefficient, $\varepsilon_{kmin} = -0.35$.

### Table 1. Calculation results of the permeability coefficients.

<table>
<thead>
<tr>
<th></th>
<th>10 MPa</th>
<th>15 MPa</th>
<th>20 MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axial Strain (%)</td>
<td>(P_u-P_f)/MPa</td>
<td>Permeability Coefficient/(10^{-11} m/s)</td>
<td>Axial Strain (%)</td>
</tr>
<tr>
<td>0.185</td>
<td>0.922</td>
<td>4.082</td>
<td>0.071</td>
</tr>
<tr>
<td>0.292</td>
<td>0.932</td>
<td>3.287</td>
<td>0.176</td>
</tr>
<tr>
<td>0.377</td>
<td>0.927</td>
<td>2.823</td>
<td>0.275</td>
</tr>
<tr>
<td>0.452</td>
<td>0.923</td>
<td>3.136</td>
<td>0.374</td>
</tr>
<tr>
<td>0.560</td>
<td>0.865</td>
<td>4.745</td>
<td>0.478</td>
</tr>
<tr>
<td>0.595</td>
<td>0.863</td>
<td>5.066</td>
<td>0.534</td>
</tr>
<tr>
<td>0.656</td>
<td>0.838</td>
<td>5.425</td>
<td>0.596</td>
</tr>
<tr>
<td>0.692</td>
<td>0.846</td>
<td>5.746</td>
<td>0.630</td>
</tr>
<tr>
<td>0.729</td>
<td>0.818</td>
<td>6.677</td>
<td>0.692</td>
</tr>
<tr>
<td>0.824</td>
<td>0.789</td>
<td>8.652</td>
<td>0.842</td>
</tr>
<tr>
<td>0.974</td>
<td>0.744</td>
<td>10.585</td>
<td>0.845</td>
</tr>
</tbody>
</table>
1.036 0.713  11.250  0.919  0.906  6.940  1.107  0.970  1.540  
1.189 0.640 25.869  1.040  0.932  6.350  1.558  0.962  1.876  
1.190 0.584 25.533  3.960  0.958 28.619  1.802  0.931  0  

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<table>
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<tr>
<td>1.036</td>
<td>0.713</td>
<td>11.250</td>
<td>0.919</td>
<td>0.906</td>
<td>6.940</td>
<td>1.107</td>
<td>0.970</td>
<td>1.540</td>
<td></td>
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<td>1.189</td>
<td>0.640</td>
<td>25.869</td>
<td>1.040</td>
<td>0.932</td>
<td>6.350</td>
<td>1.558</td>
<td>0.962</td>
<td>1.876</td>
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<tr>
<td>1.190</td>
<td>0.584</td>
<td>25.533</td>
<td>3.960</td>
<td>0.958</td>
<td>28.619</td>
<td>1.802</td>
<td>0.931</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

Figure 4. Anhydrite permeability coefficient–strain fitting curve.

4. Numerical Analysis of Tightness

4.1. Numerical Model

On the basis of the stratigraphic borehole data of the Anhui Hengtai anhydrite mine-out and the actual excavation situation in 2020, a numerical model of the mine-out was constructed using FLAC. The model was 2310 m long, 1291 m wide, and 620 m high and consisted of 781,852 grid points and 1,630,569 elements. To simplify the calculations, the strata of the model were divided into four layers from top to bottom: the Quaternary (Q) alluvium and diluvium soil, the Cretaceous (K2) glutenite, the Triassic (T2d) limestone, and the Triassic (T2d) anhydrite (Figure 5). These layers were assumed to be continuous and uniform media with self-weight. In the calculation process, the ground surface was free; the horizontal and vertical displacements of the bottom surface and the horizontal displacements of the side surfaces were fixed. Referring to the research result of Wang et al. (2018), the Mohr–Coulomb failure criterion was adopted for the soil layer, glutenite layer and, limestone layer, while the generalized Hoek–Brown failure criterion was adopted for the anhydrite layer, and the parameters are shown in Tables 2 and 3. The Moh–Coulomb failure criterion is shown in Equation (5), and the generalized Hoek–Brown failure criterion is shown in Equation (6) [4]:

$$\sigma_1 = \frac{1 + \sin \varphi}{1 - \sin \varphi} \sigma_3 + \frac{2c \cos \varphi}{1 - \sin \varphi}$$  \hspace{1cm} (5)

$$\sigma_1 = \sigma_3 + \sigma_c (m_b \sigma_c + s)^a$$  \hspace{1cm} (6)
where $m_b$, $s$, and $a$ are the Hoek–Brown failure criterion material constants, which can be calculated by Equation (7):

$$
\begin{align*}
  m_b &= \exp \left( \frac{GSI - 100}{28 - 14D} \right) m_i \\
  s &= \exp \left( \frac{GSI - 100}{9 - 3D} \right) \\
  a &= 0.5 + \frac{1}{6} \left[ \exp \left( -\frac{GSI}{15} \right) - \exp \left( -\frac{20}{3} \right) \right]
\end{align*}
$$

(7)

where $GSI$ is the geological strength index; $D$ is the disturbance factor; and $m_i$ is the Hoek–Brown failure criterion material constant.

Figure 5. Numerical model.

Table 2. Mohr–Coulomb failure criterion parameters of the anhydrite rock mass [4].

<table>
<thead>
<tr>
<th>Stratum</th>
<th>$E$ (MPa)</th>
<th>$\nu$</th>
<th>$\varphi$ ($^\circ$)</th>
<th>$c$ (MPa)</th>
<th>$\rho$ (kg/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alluvium and diluvium soil</td>
<td>19</td>
<td>0.31</td>
<td>30</td>
<td>0.01</td>
<td>2000</td>
</tr>
<tr>
<td>Glutenite</td>
<td>50,000</td>
<td>0.25</td>
<td>40</td>
<td>26.00</td>
<td>2450</td>
</tr>
<tr>
<td>Limestone</td>
<td>60,000</td>
<td>0.24</td>
<td>42</td>
<td>30.00</td>
<td>2500</td>
</tr>
</tbody>
</table>

Table 3. Generalized Hoek–Brown failure criterion parameters of the anhydrite rock mass [4].

<table>
<thead>
<tr>
<th>Parameters</th>
<th>$\rho$ (kg/m$^3$)</th>
<th>$E$ (GPa)</th>
<th>$\nu$</th>
<th>$\sigma_c$ (MPa)</th>
<th>GSI</th>
<th>$D$</th>
<th>$m_i$</th>
<th>$m_b$</th>
<th>$s$</th>
<th>$\alpha$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>2940</td>
<td>32.61</td>
<td>0.15</td>
<td>68.48</td>
<td>85</td>
<td>0.15</td>
<td>18.35</td>
<td>10.28</td>
<td>0.173</td>
<td>0.500</td>
</tr>
</tbody>
</table>

4.2. Numerical Simulation Scheme

According to the existing engineering experience, the oil storage pressure of underground sealed oil depots is usually between 0.2 MPa and 1.0 MPa, and the specific value varies according to the storage scale, storage type, cavern buried depth, groundwater level, regional engineering geological conditions, and other factors. Considering that the excavation and crude oil storage could have a certain impact on the stress distribution of the surrounding rock and then affect the strain and permeability coefficient, the tightness of the anhydrite mine-out after mining and during crude oil storage were studied through the following four schemes, as shown in Table 4.
Table 4. Numerical simulation scheme.

<table>
<thead>
<tr>
<th>Scheme</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storage pressure (MPa)</td>
<td>0</td>
<td>0.2</td>
<td>0.6</td>
<td>1.0</td>
</tr>
</tbody>
</table>

After the numerical calculations, the element strain information of anhydrite formation was output; the permeability coefficient of anhydrite formation was then calculated using the constructed permeability coefficient–strain empirical formula, and its visual–spatial distribution was created.

4.3. Tightness Analysis of the Anhydrite Mine-Out

4.3.1. Permeability Coefficient of the Surrounding Rock after Excavation

Figure 6 shows the distribution of the permeability coefficient of the surrounding rock after the excavation of the mining caverns. It can be seen in the figure that the excavation had a certain impact on the permeability coefficient of the anhydrite layer, and the permeability coefficients of the upper surface of the anhydrite layer and the corresponding part of the mine-out increased, resulting in a regional concentration. The permeability coefficients of the top and bottom layers of the mining caverns were large, and the permeability coefficients of the walls on both sides were small. The maximum value of the permeability coefficients appears at the intersection of the bottom of the mining caverns and the transportation roadways, which was approximately $4.32 \times 10^{-11}$ m/s. Considering the permeability coefficient distribution of the surrounding rock mass elements of the mining caverns, it is considered that its permeability is small and that the mine-out has good tightness.

![Figure 6. Distribution of the permeability coefficient of the anhydrite layer after excavation.](image)

4.3.2. Permeability Coefficient of the Surrounding Rock during Oil Storage

The distributions of the permeability coefficient of the surrounding rock under different storage pressures are shown in Figures 7–9. The maximum permeability coefficients of the surrounding rock under storage pressures of 0.2 MPa, 0.6 MPa, and 1.0 MPa are $4.3181 \times 10^{-11}$ m/s, $4.3189 \times 10^{-11}$ m/s, and $4.3191 \times 10^{-11}$ m/s, respectively. In addition, the permeability coefficients of the upper surface of the anhydrite layer and the corresponding part of the mine-out increased regionally, but the overall growth range was small. The permeability coefficients in the top and bottom layers of the anhydrite mining caverns were large, while the permeability coefficients of the sidewalls on both sides were small. The maximum permeability coefficient appeared at the intersection of the mining caverns and transportation roadways, which is worthy of special attention during an oil storage operation.
Figure 7. Distribution of the permeability coefficient of the anhydrite layer under 0.2 MPa storage pressure.

Figure 8. Distribution of the permeability coefficient of the anhydrite layer under 0.6 MPa storage pressure.

Figure 9. Distribution of the permeability coefficient of the anhydrite layer under 1.0 MPa storage pressure.

The curves of the maximum permeability coefficient of the surrounding rock under four different storage pressures of 0 MPa, 0.2 MPa, 0.6 MPa, and 1.0 MPa with the storage pressure can be drawn, as shown in Figure 10. As can be seen in the curves, with the continuous increase in storage pressure, the maximum permeability coefficient of the mine-out also increased, but the increase was small. In addition, when the storage pressure reached a certain value, the growth rate of the maximum permeability coefficient also began to slow. Comprehensive analysis of the size and distributions of the permeability
coefficients of the rock surrounding the mine-out suggests that the mine-out has good tightness during oil storage.

![Figure 10](image_url)

**Figure 10.** Curve of the maximum permeability coefficient of the surrounding rock mass elements under different storage pressures.

5. Discussion

In the field of seepage—stress coupling of underground space rock masses, previous research has mostly studied the evolution law of the strength, deformation, and permeability of rock under simulated natural stress and seepage environments in laboratory tests, which is rarely applied in practical engineering. In this study, the evolution law of the stress, strain, and permeability coefficients of anhydrite rock during compression failure were evaluated using triaxial compression tests considering seepage, and the corresponding relationship between the permeability coefficient and the strain of anhydrite rock was constructed. On the basis of the findings, the tightness of the abandoned anhydrite mine-out space after excavation and when used for crude oil storage was studied, enriching the research results of anhydrite mine-outs, which further confirms the feasibility of using an anhydrite mine-out for oil storage and provides an important reference for the tightness evaluation of an underground storage space.

The numerical results show that the maximum permeability coefficient of the anhydrite mine-out increased with the increase of crude oil storage pressure, and the growth rate began to slow when the storage pressure reached a certain value. Overall, the permeability coefficient was small, with a magnitude of $1 \times 10^{-11}$ m/s. This can provide a reference for the practical engineers and designers to calculate the crude oil loss rate and evaluate whether the anhydrite mine-out is suitable for crude oil storage. However, there are still many problems in this study’s proposed method of evaluating the tightness of the anhydrite mine-out, which needs to be further improved and perfected. For example, in this study, the anhydrite rock was regarded as a homogeneous material, without considering factors such as rock fracture and rock dispersion, so there is still a certain gap between the hypothetical conditions and the actual situation. Moreover, this study only considered the tightness of the anhydrite mine-out under excavation unloading and crude oil storage loading conditions and did not consider the cyclic loading and unloading of crude oil, which occurs in the actual storage operation. In addition, the permeability coefficient of
the anhydrite formation was mainly calculated using the empirical permeability coefficient–strain formula combined with numerical simulation, and the accuracy of the calculation results needs to be demonstrated. These problems should be considered, and further research is needed to make the research results closer to the actual situation of the project. Furthermore, the tightness monitoring of the anhydrite mine-out used to store crude oil is crucial and should be considered in future studies. Bouchaala et al. (2019a, 2019b) showed that fracture development in rocks can be monitored through unconventional seismic attributes, such as seismic attenuation [46,47]. Furthermore, Takougang et al. (2019) suggested a new workflow based on the Reverse Time Migrated (RTM) to monitor fractures around reservoir zones [48]. Therefore, seismic monitoring may be a good option for monitoring natural tanks for crude oil storage.

6. Conclusions

By combining lab tests and numerical simulations, this paper investigated the tightness of anhydrite mine-out for crude oil storage under different working conditions. Through the above analysis, the following conclusions can be drawn:

(1) With an increasing axial load, the permeability coefficients of the anhydrite samples generally decreased first and then increased, and the variation amplitude decreased with increasing confining pressure. When the confining pressure was greater than 15MPa, the permeability coefficient of the anhydrite rock was 0.

(2) After excavation, the maximum permeability coefficient of the anhydrite mine-out appeared at the intersection of the bottom of the mining caverns and the transportation roadways. The permeability coefficients of the upper surface of the anhydrite layer and the corresponding part of the mine-out increased regionally, but its range was small, and the mine-out had good tightness.

(3) During oil storage, although the maximum permeability coefficient of the anhydrite mine-out increased with increasing storage pressure, the overall value was still small. After the storage pressure reached a certain value, the growth rate of the maximum permeability coefficient gradually slowed, and the mine-out had good tightness.

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References


12. Fu, D. Research on strength timeliness of anhydrite rocks immersed in distilled water and crude oil. Master’s Thesis, China University of Geosciences (Beijing), Beijing, China, 2017. (In Chinese)


