Assessing the water-sealed safety of an operating underground crude oil storage adjacent to a new similar cavern – A case study in China

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A R T I C L E   I N F O

Keywords:
Underground water-sealed oil storage
Assessment of water-sealed safety
Numerical simulation
Monitoring data
Safety separation distance

A B S T R A C T

Siting a new underground water-sealed crude oil storage adjacent to an existing one is a potential way to increase the capacity of strategic energy storage. The study presented herein is a comprehensive case study to assess the water-sealed safety on this topic using monitoring data and numerical analyses. A three-dimensional geo-hydrological model was built based on a specific project calibrated using field monitoring data. The influence of the new construction on the water-sealed safety of the operating cavern was examined with numerical models by considering the effects of the layout of the new cavern. Three indicators were used to quantitatively assess the water-sealed safety of the operating cavern. The result shows that it is feasible to set a storage cavern adjacent to an operating one. The safety separation distance between two projects without a vertical water curtain can be set to 200 m. In addition, vertical water curtain was discussed to shorten the safety separation distance in practical (e.g. with site conditions limitation). The achieved results can be used to guide the design and construction of similar projects.

1. Introduction

Storing crude oil in underground storage caverns has been established as being cost-effective in the case of strategic petroleum reserves with improved safety, reduced land use, and low-maintenance cost compared to other alternative depots (Morfeldt, 1983; Bergman, 1984; Lu, 1998). Many underground water-sealed storage caverns have been constructed and are currently in good operational conditions. These constructed oil storage caverns are usually located in areas with good engineering geological and hydro-geological conditions (e.g. in areas with a relatively intact rock formation, such as granite, or with adequate water supply). These conditions are also preferred for siting new underground oil storage caverns (Hoshino, 1993; Mohanty and Vandergrift, 2012). To expand the existing storage capacities, it is cost-effective to build a new underground crude oil storage cavern adjacent to an operating one. It could allow the sharing of supporting facilities and coordination of operations, and could thus lead to cost savings in management. However, the safety of the operating cavern may be affected by the excavation of the new cavern. Therefore, the water-sealed safety assessment of an operating underground crude oil storage cavern is important to ensure the performance of the operating project and to optimise the layout of proposed project.

Numerous studies have been conducted in assessing the rock stability and water-sealed safety of a single underground oil storage cavern (Kiyoyama, 1990; Lee and Song, 2003; Benardos and Kaliampakos, 2005). Specifically, the stability of the cavern has attracted the attention of many researchers (Lee et al., 1997; Mohanty and Vandergrift, 2012). In addition to rock stability, the water-sealed performance plays a critical role for the safe operation of the underground water-sealed storage cavern (Li et al., 2016). The performance of the underground water-sealed storage cavern, which is determined by a sustained water curtain, has been analysed in many previous studies (Åberg, 1978; Goodall et al., 1988; Chung et al., 2003; Ji et al., 2017). Different numerical simulation methods have been proposed for the study of the water curtain system performance (Ivars, 2006; Li et al., 2014; Ren et al., 2016). Theoretical analyses (Liang and Lindblom, 1994; Kim et al., 2007; Kim et al., 2012; Ghotbi Ravandi et al., 2016), model experiments (Li et al., 2009; Jo and Lee, 2010) and field data analyses (Jo and Lee, 2010; Wang et al., 2015), have also been used to analyse the underground seepage field and water-sealed reliability for underground crude oil storage caverns.

There have only been a limited number of documented application examples of siting new water-sealed crude oil storage cavern adjacent to an operating one worldwide (Wang et al., 2016). However, for large-
scale oil storage cavern, which is required to meet rigorous safety standards, significant attentions need to be paid to mitigate the influence of the proposed project setting to the operational safety of the existing project. Therefore, significant engineering questions arise on how the excavation activities of the new project change the groundwater level within the influenced area, and on whether the water inflow of the operating project will decrease owing to the new excavation. Furthermore, it is also interesting to study the change in the vertical hydraulic gradient above the operating project, and the effects of blasting vibrations caused by construction activities to the water-sealed safety of the operating project (Ramulu et al., 2009).

The objective of this study is to propose a method to evaluate the water-sealed safety of an operating project, and to provide recommendations on the most suitable location for the construction of the proposed project. In this study, field monitoring data (water inflow and groundwater level variation during the entire construction period of the operating project) were used to guide the assessment of the water-sealed safety of the proposed project. A set of assessment matrices with three major factors were adapted to access the water-sealed safety of an operating underground crude oil storage cavern influenced by the excavation of a new, similar cavern. The three factors included the groundwater level, the water inflow of the operating project, and the vertical hydraulic gradient. The feasibility of setting a storage cavern adjacent to an operation one was confirmed. And a safety separation distance between the operating and proposed projects is presented.

2. Site description

2.1. Introduction to operating and proposed projects

The underground crude oil storage cavern in this study is located on the Southeast coast of China (Fig. 1). In this study, the operating underground water-sealed oil storage project has a capacity of $5 \times 10^6$ m$^3$. It consists of storage caverns, access tunnels, and a water curtain system (Fig. 1). Based on the field investigation, the geological conditions around the operating project are particularly good. Furthermore, the matched supporting facility has been built for the operating project. Thus, the proposed project is planned to be built on the north of the operating project (Fig. 1). With the contribution of the proposed project, the storage capacity will increase to $8 \times 10^6$ m$^3$. It could also be a cost-saving practice for sharing the supporting facility and coordinating operations. The length of ten constituted storage horseshoe-shaped caverns ranges from 860 to 960 m. The caverns are located at depths ranging from $-30$ to $-60$ m. The cavern has a width of 20 m and height of 30 m. The access tunnel is horseshoe-shaped and has a width of 8.5 m and height of 7.5 m. The horseshoe-shaped water curtain tunnel has a width of 5 m and height of 4.5 m, and is designed to be 25 m above the storage caverns, according to the Code for Design of Underground Oil Storage in Rock Caverns (GB 50455-2008, 2008).

A similar underground storage project with a capacity of $3 \times 10^6$ m$^3$ is being planned in the northwest direction of the operating project. The proposed project will have six storage caverns with the same section size as those of the operating project. The water-sealed safety of the operating project must be ensured under the condition of proposed project excavation. For this reason, the selection of the location of the proposed project is a crucial factor for the implementation of the proposed project setting. When the distance between the operating and proposed projects is too small, there may be safety and environmental risks owing to the leakage of stored oil. Or, the location of proposed project might encounter areas with unsatisfied geological conditions, which will significantly increase the investments.

2.2. Engineering geology

The study area is a hilly terrain with no major faulty structure, and has a favourable regional stability. Quartz veins are exposed at a local scale with the strike of northwest. The geological substrate primarily comprises granite rocks from the Carboniferous Ceshui formation (Cc1) to the Quaternary Pleistocene (Qw) age. The intrusive rock is mainly comprises granite of the late Jurassic system (J3), and is geologically and sequentially divided into two units, namely the Shipailin unit (J3S), and the Guanyinmiao unit (J3G) (Fig. 2a). The degree of rock weathering from the surface is categorised as follows: completely weathered, intensely weathered, moderately weathered, and weakly weathered.
zones, based on the information in Table 1.

The underground water-sealed cavern is located in a weakly weathered rock (Fig. 2b). For the rock mass in the study area, the average value of the saturation uniaxial compressive strength, cohesion, internal friction angle, and rock modulus of elasticity is 72 MPa, 22 MPa, 45°, and 41 GPa, respectively.

The spatial distribution and the behaviour of fracture exert the controlling action to the cavern stability and water-sealed safety (Li et al., 2016). The fracture behaviour and spatial distribution (i.e., density of fracture) vary with depth. The fracture in intensely and moderate weathered zones is mainly crossed-net fractures. Fractures in weak weathered and un-weathered zones are mainly vein fissures with major strikes. Fig. 3 shows the characteristics of the dip and angle of fracture at different depths. In general, the attitude of the surface fracture presents a random distribution (Fig. 3a). The fractures at the level of the water curtain system and main caverns both show a relatively concentrated distribution with major dip directions in the ranges of 60°–80° and 210°–260° (Fig. 3b and Fig. 3c). For most of the fractures, the dip angle is larger than 60°. The axis direction of the water curtain boreholes and the cavern of operating project is 70° along the northeast, thus intersecting fracture strikes at large-angles (Fig. 2a). Thus, it will benefit the cavern stability. Meanwhile, the axis of the water curtain boreholes is parallel to the axis of the main cavern, ensuring that the major fractures are vertically crossed by the boreholes of the water
curtain. In addition, the angles of the fractures are steep. These will benefit the realisation of the connection among fractures, and thus guarantee the water-sealed safety.

Rock classification in the study area is performed according to Standard for Engineering Classification for Rock Mass (GB 50218-2014, 2014) (Table 2). The classification for rock mass in this standard is based on the BQ system (the calculation of BQ is listed in Table 2). The BQ system is a rock mass classification system used in China that is similar to the international RMR and Q systems. The BQ system divides all rock masses into five classes. The boundary value of each class could be analysed based on the numerous civil engineering case histories in China, as listed in Table 2. The relationships between the BQ, RMR, and Q systems have been studied in detail previously (Liu et al., 2017). The proportion ratios of level I and level II rock masses for the operating and proposed projects are approximately equal to 70%. Generally, the engineering geology provides excellent conditions for the construction of underground crude oil storage caverns.

2.3. Hydrogeology

The groundwater is stored in pores and fractures. The Quaternary pore water is mainly found in the covering layer. There is water in the bedrock fissure under the covering layer. The fissure water is categorised into two types, namely, net fissure water, and vein fissure water. The water storage capacity is rated as weak-to-medium. In this area, the annual precipitation ranged between 1426.3 mm and

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**Table 1**

<table>
<thead>
<tr>
<th>Degree of weathering</th>
<th>Field characteristics</th>
<th>Parameters of degree of weathering</th>
</tr>
</thead>
<tbody>
<tr>
<td>Un weathered</td>
<td>Fresh rock, occasionally weathered traces</td>
<td>Velocity ratio ($K_v$) 0.9–1.0</td>
</tr>
<tr>
<td>Weakly weathered</td>
<td>Structure has been rarely altered, only the surface of the joint is slightly discoloured. There are a few weathered cracks</td>
<td>Weathered coefficient ($K_f$) 0.9–1.0</td>
</tr>
<tr>
<td>Moderately weathered</td>
<td>Structure has been partly damaged. There are secondary minerals and weathered fissures along the joint surface. The rock is cut into rock blocks.</td>
<td>0.8–0.9</td>
</tr>
<tr>
<td>Intensely weathered</td>
<td>Most of the structure is damaged. Mineral composition has been significantly changed. The weathered fissures are well developed. The rock mass is broken</td>
<td>0.6–0.8</td>
</tr>
<tr>
<td>Completely weathered</td>
<td>The structure has been completely destroyed. There still have the residual structural strength</td>
<td>&lt; 0.4</td>
</tr>
</tbody>
</table>

Note: $K_v$ is the velocity ratio of weathered rock to fresh rock.

$K_f$ is the uniaxial compressive strength ratio of weathered rock to fresh rock.

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![Fracture contour diagram of the study area](image-url)

**Fig. 3.** Fracture contour diagram of the study area.
Table 2
Classification of engineering rock mass types for the operating and proposed projects.

<table>
<thead>
<tr>
<th>Elevation (m)</th>
<th>Classification of engineering rock mass</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Level I</td>
</tr>
<tr>
<td>Operating project</td>
<td>Proposed project</td>
</tr>
<tr>
<td>0 to −10</td>
<td>25.90%</td>
</tr>
<tr>
<td>−10 to −20</td>
<td>27.57%</td>
</tr>
<tr>
<td>−20 to −30</td>
<td>35.14%</td>
</tr>
<tr>
<td>−30 to −40</td>
<td>38.69%</td>
</tr>
<tr>
<td>−40 to −50</td>
<td>27.99%</td>
</tr>
<tr>
<td>−50 to −60</td>
<td>30.97%</td>
</tr>
<tr>
<td>−60 to −70</td>
<td>35.14%</td>
</tr>
<tr>
<td>Average</td>
<td>31.60%</td>
</tr>
</tbody>
</table>

\[ BQ = 100 + 3R_c + 250K_v + \left( \frac{V_{pm}}{V_{pr}} \right)^2 \]

*\( R_c \) is the saturated uniaxial compressive strength, \( V_{pm} \) is the elastic wave velocity of rock mass, and \( V_{pr} \) is the elastic wave velocity of rock.*
2399.6 mm between 2005 and 2015. Additionally, heavy rainfall tends to occur between April and September, accounting for 80% of the annual precipitation.

The groundwater level varied with topography and season. The annual variation of the groundwater level ranges approximately between 0.5 m and 4.0 m (Fig. 4). The recharge conditions include: 1) natural recharge (precipitation and surface water), and 2) artificial recharge (water injection of the water curtain system). The discharge condition is associated with the water inflow caused by the excavation of the main caverns, the access tunnel, and the water curtain tunnel.

Three representative boreholes are selected to show the permeability of the study area (Fig. 1a). ZK 4 is located in the area of the operating project. ZK12 and ZK 14 are located in the proposed project. The results of the pumping and the water injection tests show that the permeability of the rock mass of the cavern elevation varies from $10^{-7}$ to $10^{-9}$ m/s and decreases with depth (Fig. 5). The wave velocity shows an increasing trend with depth, thus indicating a decreasing permeability with depth.

3. Method

3.1. Field monitoring

A large amount of data on groundwater level variation and water inflow will be collected during the construction of the proposed cavern. Thus, the variation characteristics of different phases of the operating project could be summarised. As the proposed project should be set near the operating project, the geological and hydrological conditions should be almost the same for the proposed and the operating projects. Based on the guiding concept of engineering analogy analysis, the variation laws of the operating project can reflect the variation laws of the proposed project to a certain extent. Subsequently, it could be a guidance of the design and construction of the proposed project.

The dynamic variation in the groundwater level was selected as one of the factors used to assess the water-sealed safety. Subsequently, some exploration boreholes were drilled during the investigation stage. The water levels in these boreholes were monitored. However, during the cavern excavation, these boreholes will lose their efficacy because they will be buried. Thus, these boreholes were named temporary monitoring boreholes in this study (represented by ZK, as shown in Fig. 2a). Groundwater level variations were collected in 16 representative temporary monitoring boreholes. In addition, twelve permanent boreholes were drilled to reflect the water level variation around the caverns in the construction and operation periods (represented by OH). Additionally, water inflow was selected as a factor used to assess the water-sealed safety water inflow. Water inflow and its spatial distribution play important roles in the assessment of the water-sealed safety (Wang et al., 2015). In underground water-sealed storage caverns, water inflow should be considered from two perspectives. From one perspective, it can be treated as a harmful factor for the stability and safety of operations when the water inflow is very large (Wei et al., 2017). From another perspective, however, it may be an indication of water-sealed failure if the water inflow is too small (Shi et al., 2018). Thus, the total water inflow of the reservoirs was collected.

The main purpose of the field monitoring method is to assess the water-sealed safety of the operating storage project before the proposed cavern excavation. This is a precondition to assess the water-sealed safety of the operating project after the excavation of the proposed project. Additionally, the field monitoring data could be used to calibrate the numerical simulation model to make the assessment reasonable.

3.2. Numerical simulation

3.2.1. Theoretical model

The COMSOL MULTIPHYSICS was to solve this cross-scale problem with finite element method. The size of the study area is 2200 m × 2200 m. It is large enough to satisfy the condition of the representative elementary volume (REV) (Baghbanan and Jing, 2007). Therefore, the study area is considered as a heterogeneous, equivalent continuous medium, with a permeability coefficient that varies with depth. The operating project in this study is a strategic oil storage cavern. The oil will be stored in the cavern for many years without extraction. In the operating phase, the seepage field around the operating
project could be regarded as a relative equilibrium state. Meanwhile, for the proposed project, the water curtain system should be pre-installed before the proposed cavern excavation to maintain the stability of the groundwater above the proposed project. Subsequently, the seepage field around the proposed project could also be regarded as a relative equilibrium state. Thus, the steady state model could approximately reflect the variation rules of the operating project caused by the proposed project. In addition, the numerical model should be calibrated with field monitoring data before it is used to assess the water-sealed safety of the operating storage project under the condition of the proposed cavern excavation. The seepage discharge velocity is related to the pore water head, including the pressure head in accordance to Darcy's law (Kjørholt and Broch, 1992):

\[ v_i = -\frac{1}{\gamma_w} \frac{\partial (p + \gamma_w z)}{\partial x_i} \]  

(1)

where \( k \) is the permeability coefficient, m/s, \( v_i \) is the discharge velocity of seepage, m/s, \( \gamma_w \) is unit gravity, N/m³, \( p \) is the pore pressure, MPa, \( z \) is the vertical coordinate, m, and \( x_i \) is the distance along the X coordinate axis, m.

Combining the above equation with the principle of mass conservation and effective stress, the basic governing equation can be described as follows:

\[ S_a \frac{\partial p}{\partial t} + V \cdot \left( -\frac{k}{\gamma_w} V(p + r_w z) \right) = Q_s - \frac{\partial}{\partial t} (\nabla \cdot \mathbf{u}) \]  

(2)

where \( S_a \) is the storage coefficient of the rock mass, \( t \) is time, \( s \), \( Q_s \) is the
source item of volume, m³, \( \varphi \) is porosity, and \( u \) is the velocity vector, m/s.

The first boundary condition is the boundary of fixed water level expressed by Eq. (3), and the second boundary condition is the boundary of fixed flow expressed by Eq. (4).

\[
V \cdot (\rho u) = Q
\]  

(3)
\[ \tau = -k(\nabla \rho + \rho g \nabla D) \]  
(4)

where \( \rho \) is the density of fluid, kg/m\(^3\), and D is the elevation, m.

### 3.2.2. Numerical model

The length, width, and height of the model were 2200 m, 2200 m, and 470 m, respectively (Fig. 6a). The model fully considered the far field boundary condition. The model contained 482,037 elements. Direction X was the direction of the axis of the cavern. The diameter of the water curtain hole was only 100 mm, and was much smaller than any other part of the structure (cavern, access tunnel, and water curtain tunnel). Therefore, an equivalent substitution was used to apply the pressure provided by the water curtain borehole. The access tunnels were neglected owing to the smaller water inflow compared to the caverns with the guide of the field monitoring data. The geometric model is shown in Fig. 6a. Additionally, sensitivity analyses were conducted on various distances between the operating and the proposed projects (i.e. 50, 100, 150, 200, 250, and 300 m) on the water-sealed safety of the operating project.

The surrounding and bottom boundaries of the model were set as impermeable boundaries. The boundary condition of the cavern filled with oil is shown in Fig. 6b. According to a previous study (Shi et al., 2018), to ensure the equivalence of the water curtain holes, the inner pressure in the water curtain tunnel was assumed to be 0.22 MPa. The pressure boundary condition of the proposed project after excavation was assumed to be 0 MPa. The boundaries of the caverns filled with oil satisfy the second boundary condition, namely, the boundary of fixed water level, as shown in Fig. 6b. To be specific, the pressure of the boundary EF is 0.2 MPa. The pressure of the boundary CE and DF was obtained based on the function of \( \rho_{\text{water}} g y + 0.44 \) MPa. Moreover, the pressure of the boundary AB was 0.45 MPa. The surrounding and bottom boundaries of the numerical model satisfied the second boundary condition, and the boundary of fixed flow. The change of permeability with depth was described by fitting the measured data. The relationship of permeability and depth is shown in Fig. 7.

### 4. Assessment result

#### 4.1. Field monitoring assessment

**4.1.1. Groundwater level variation**

Figs. 8 and 9 show the plotted monitored data of groundwater level variations over time in the study area. The water level variations in the temporary monitoring boreholes during excavation are shown in Fig. 8. The last day of the temporary boreholes was August 30, 2015, which was after the completion of all the excavations. It can be found that the majority of the groundwater level can maintain a relatively stable state close to the initial condition except of the four monitoring boreholes (ZK 16, 17, 22, 24). For ZK 16, 17, 22, and 24, an interesting phenomenon observed was that the locations of the four boreholes were all around the centre of the operating project. This implied that the influenced scope of groundwater caused by excavation was mainly around the centre of the operating project. Meanwhile, the boreholes ZK 16, 17, 22, and 24 can also maintain a relatively high water level. The elevation of the groundwater level in the ZK 16, 17, 22, and 24, were approximately 65, 75, 68, and 160 m, respectively, which is much higher than the water curtain system (EL. –5 to 0 m). Therefore, it can also guarantee the water-sealed safety. It can be inferred that the stability of the groundwater level can be maintained with the function of the water curtain system above that of the proposed project during the construction period.

Twelve permanent boreholes were drilled to reflect the water level variation around the caverns in the construction and operation periods. Water level variations in the permanent monitoring boreholes drilled during the construction period are shown in Fig. 9. It can be inferred that the stability of the groundwater level can be maintained with the function of the water curtain system above the proposed project during the construction period. Under operating conditions (whereby the cavern is filled with crude oil), the caverns produce an internal pressure (Fig. 6) which helps maintain the stability of the water level.

From the above results, it can be concluded that the groundwater level around the storage cavern could hardly be influenced by the excavation. However, more attention should be paid to the groundwater variation in the area around the centre of the proposed storage project.

**4.1.2. Water inflow**

Fig. 10 shows the variation in the water inflow of the operating project during the entire construction time. The variation trend of the
water inflow during the construction period can be divided into three stages: disturbance period caused by construction, relative steady stage during construction, and water-decreasing period induced by grouting. During the disturbance period, the water inflow fluctuated between 1900 m$^3$/d and 4600 m$^3$/d. The disturbance period contained the first and second slicing of the cavern. The fluctuation of water inflow is mainly caused by the constantly emerging seepage channels owing to excavation. At the time when the excavation of the cavern's second slice...
was nearly completed, the water inflow became steady (relative steady stage during construction). The water inflow decreased as the pressure of the water curtain boreholes decreased. In this period, the seepage channel had been almost exposed. Thus, the seepage field was similar to the operating condition. The relatively stable water inflow in this phase could indicate the water-sealed reliability of the storage cavern. After the excavation of all the caverns, grouting would be applied. The water inflow before grouting was 1700 m$^3$/d and dropped to 700 m$^3$/d owing to the effects of grouting. Given the similarity of the conditions of the two constructions (proposed and operating project), the variation mode of the operating project in the construction period can be used to guide the proposed project. The GB 50455-2008, 2008 suggests that the daily water inflow after grouting should not be higher than 100 m$^3$/d every 1 × 10$^6$ m$^3$, which indicates that the operating project water inflow should not be higher than 500 m$^3$/d. The water inflow in this study is slightly higher than the suggested value owing to the sufficient water supply conditions in Southern China (average annual precipitation of 2000 mm). The water inflow variation indicated that the water-sealed reliability for the operating project was guaranteed. Additionally, it could be suggested that more attention should be paid on the water inflow variation of the third excavation slicing for the assessment of water-sealed reliability.

### 4.2. Numerical simulation assessment

#### 4.2.1. Model calibration

The stable water inflow after the operating project excavation was approximately 1700 m$^3$/d (Fig. 10). Based on the water inflow data, we calibrated the numerical model that represented the condition after the operating project excavation by adjusting the seepage parameters and boundary conditions. With the calibrated numerical model, we studied the influence of the proposed project excavation on the operating one. Thus, it is reasonable to use this numerical model to study the water-sealed safety of the operating project in the case of the excavation of the similar storage cavern nearby.

#### 4.2.2. Groundwater level

Numerical simulations (Fig. 11a, b) show that the groundwater level will maintain its stability. Therefore, the water curtain above the proposed project will function properly (there will be a small conical zone of the water pressure depression above the proposed project. Although this will not influence the operating project, it will still be discussed in the subsequent section). However, the crucial question is whether the water curtain system failure of the proposed project will influence the water-sealed safety of the operating project. For this purpose, a series of numerical simulations were conducted to study the variation in the groundwater levels in the absence of a water curtain system above the proposed project. The variations of the groundwater levels are shown in Fig. 11c–f, including the areas representing the cone of depression. It is found that a larger cone of depression will be formed in the case where there is no water curtain system is set above the proposed project. Additionally, the cone of depression exhibits little variation with the variation in the distance between the two projects. However, above all, the larger scope of the depression cone cannot impact the groundwater level above the operating project. In addition, the experience of the Huangdao underground water-sealed oil storage project (located in Shandong Province, China, with a capacity of 3 × 10$^6$ m$^3$) suggests that the traditional view that the water-sealed effect is the decisive factor in the success of the underground cavern construction may not be proper (Li et al., 2016). An example is provided to show that even if the groundwater level decreases during the construction, the project can still work well to form an airtight cavern by applying the water curtain treatment after the construction of the main cavern. Therefore, it is concluded that the setting of the proposed project will not significantly affect the groundwater level above the operating project.

#### 4.2.3. Water inflow

It is assumed that after the excavation of the proposed project, the boundary of the tunnels and caverns will be subjected to a pressure of 0 MPa rather than the original subsurface water pressure. This may influence the original seepage field. Such a shift in the seepage field may impact the operating project and pose a leakage risk. Among the ten existing caverns in the operating project, cavern #1 (Fig. 6) is the nearest cavern to the proposed project. Thus, it will be subjected to a dramatic shift in the seepage field around it and will face a considerable leakage risk. Therefore, the focus of the leakage risk assessment in this study is on cavern #1. The change of the seepage field around the cavern will certainly induce the water inflow towards the cavern. On the other side, the decreases of the cavern's water inflow will reflect the extent of the seepage field variations. The variations in the water inflow of cavern #1 owing to the proposed project constituted one of the chosen factors used to evaluate the water-sealed safety of the operating project. When an empty cavern is constructed near the operating cavern #1, the water inflow of cavern #1 will certainly decrease. As the distance between them increases, the water inflow of cavern #1 will approach the level as the case where the proposed project is not excavated at all. Table 3 shows the water inflow of cavern #1 for different separating distances between the operating and proposed project set at 50 m, 100 m, 150 m, 200 m, 250 m, and 300 m. The water inflow of cavern #1 will become closer to the un-excavated condition as the distance between the two projects increases (Table 3). The conclusion is that with a sufficient distance between the two projects, the influence of the proposed project on the seepage field around the operating project will be insignificant.

#### 4.2.4. Vertical hydraulic gradient

The first accepted hydraulic gradient criterion for cavern storage of petroleum was proposed in 1977 (Åberg, 1978), and defined the following condition: $I_0 > 1$ ($I_0$ is the vertical hydraulic gradient). At that time, the sufficient condition of the he sufficient condition of lack of leakage for the case of storage caverns with no-lining was also studied (Chi-Whan, 1987). The result showed that a sufficient condition was attained when the vertical hydraulic gradient was greater than zero. Subsequently, criteria were proposed such that the water pressure gradients along all possible escape paths were positive (Goodall et al., 1988). The sufficient condition was used in the analyses of this study.

Based on discussions on groundwater level variations, it can be considered that the water-sealed conditions could be satisfied for both scenarios (the water curtain system loses efficacy or functions properly). In this case, only the scenario at which the water curtain system loses efficacy is discussed. Fig. 13 shows the vertical hydraulic gradients with the proposed un-excavated project in the two typical sections (the location of the two sections is shown in Fig. 12). Fig. 13b–f shows the vertical hydraulic gradients without the water curtain above the

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**Table 3** Water inflow at different separation distances of cavern #1 (operating project).

<table>
<thead>
<tr>
<th>Proposed project (un-excavated case)</th>
<th>Distance between the operating and proposed projects (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water inflow (m$^3$/d)</td>
<td>50</td>
</tr>
<tr>
<td>61.8</td>
<td>29.2</td>
</tr>
</tbody>
</table>
Fig. 12. Cloud map of vertical hydraulic gradient at an elevation of −5 m (25 m above the caverns).
Fig. 13. Vertical hydraulic gradient at different elevations at two typical sections of the proposed excavated project (1–1′, 2–2′).
proposed project in two typical sections. Different distances between the operating project and the proposed project (50 m, 100 m, 150 m, 200 m, 250 m, and 300 m) were studied. The vertical hydraulic gradient above the operating project will decrease as a result of the excavation of the proposed project. Meanwhile, the vertical hydraulic gradients at different levels of the two sections above the operating project are larger than zero. Obviously, the vertical hydraulic gradient around the operating project can satisfy the condition of water-sealed safety. The gradients around cavern #1 (Fig. 6) will increase when the distance between the two projects increases. When the separation distance reaches 200 m, the excavation of the proposed project has already merely influenced the vertical gradient above the operating project. Thus, the case of 250 m has been omitted in Fig. 13. Five measured lines were set above the caverns of the two projects at the elevations of −25 m, −20 m, −15 m, −10 m, and −5 m. It was also found that at a certain separation distance, the vertical hydraulic gradient for the measured line set at 25 m above the caverns was the smallest among the five measured lines studied herein. Thus, only the cases where the gradients were at the −5 m level (25 m above the caverns), and with a water curtain above the proposed project needed to be studied (Fig. 13). Evidently, the vertical hydraulic gradients around the operating project can satisfy the condition of water-sealed safety.

4.3. Safety separation distance

In summary, the water-sealed safety of the operating and the proposed projects will be maintained based on some measurements, such as the functionality of the water curtain system, and a specific separation between the two constructions. As stated above, cavern #1 is mostly influenced by the proposed project excavation. The lowest groundwater level above cavern #1 is then used to quantitatively represent the groundwater level above the operating project. The minimum vertical hydraulic gradient above cavern #1 is used to quantitatively represent the vertical hydraulic gradient of operating project (Fig. 14). According to the Code for Design of Underground Oil Storage in Rock Caverns (GB 50455–2008, 2008), the vertical distance between lowest groundwater and cavern crown should larger than 35 m to guarantee the water-sealed safety (Fig. 14). The vertical distance between the lowest groundwater level and the crown of cavern #1 yielded a positive correlation with the separation distance between the two projects, as did the vertical hydraulic gradient above cavern #1. Even when the separation distance between the two projects was 50 m, both the vertical distance between the lowest groundwater level and the crown of cavern #1 and the vertical hydraulic gradient above cavern #1 could guarantee the water-sealed principle (Qiao et al., 2017).

For the water inflow, cavern #1 could nearly recover to the condition before the excavation of the proposed project when the separation distance was 200 m. Based on a comprehensive consideration, the water-sealed safety of the operating project will not be influenced when the separation distance is 200 m or larger.

5. Discussion

Based on the above analyses, the water-sealed reliability of the operating project can be ensured. Furthermore, the above analyses could provide an insight to the assessment of the water-sealed safety of an operating underground crude oil storage adjacent to a new similar cavern. It could also be promoted to the expansion of other similar storage caverns. To be specific, to assess the water-sealed safety of the operating project, field monitoring and numerical simulation could be used. Groundwater level, water inflow, and vertical hydraulic gradients, could be used as the assessment indicators. The numerical simulation model should be calibrated with field monitoring data to guarantee the dependability of the model. In addition, the field monitoring data variation of the operating project can direct the design and construction of the proposed project.

However, it should be noticed that there exists a small cone of depression above the proposed project, even if the water curtain above the proposed project functioned well. The topographic variation of the study area is shown in Fig. 15. As the groundwater level varies with topography, it can be concluded that the formation of the cone of depression is mainly owing to the lower groundwater level above the proposed project (Fig. 15).

Therefore, at a distance of 200 m at which the water-sealed safety of the operating project is guaranteed, the groundwater level above the proposed project (related to the relative position of the two projects in the X direction) should be considered. A series of numerical simulations (as a function of distance along the X direction, set at 20 m, 40 m, 60 m, 80 m..., 180 m, 200 m) were conducted to identify a proper position in the X direction to guarantee the water-sealed performance around the proposed project. Those simulations showed that there would be no conical depression above the proposed project when it was moved by 180 m towards the negative X direction (Fig. 16a). The vertical hydraulic gradients above the caverns of the two projects were all larger than zero under such conditions (Fig. 16b). It is concluded that water-sealed safety can be guaranteed by moving the proposed project by 180 m towards the negative X direction.

The above analyses could theoretically provide an insight in the feasibility of the construction of a new project adjacent to an operating...
one. In practice, some recommendations could be provided for practical constructions:

1) Based on some simplifying assumptions adopted in this study, like equivalent continuum modelling or homogenous media, the large-scale fault between the operating and proposed project was ignored. Meanwhile, the result indicated that the water-sealed safety could be guaranteed if there were no large-scale faults between the two projects. Thus, in practice, more detailed geological surveys along the areas between the operating and the proposed projects will help identify potential seepage channels between the two constructions. The geological sketch of the cavern and access tunnel nearest to the proposed project (cavern #1 in this study) could be helpful in providing the information of potential seepage channels. Specifically, the boreholes of the engineering investigation phase should be laid out based on the information (e.g. the zone with great fracture density) reflected in the geological sketch stated above.

2) According to the above analyses, the separation distance of 200 m is a safety distance for the water-sealed property of the operating project in this study. However, in some special situations, the separation distance between the two projects may not reach 200 m given the geological and hydro-geological constraints. In these cases, a vertical water curtain system may be helpful to decrease the safe separation distance between the two projects. Some numerical experiments have been conducted to discuss the function of the vertical water curtain. The model here will not be described further. Only the results are shown in Fig. 17. The lowest groundwater above cavern #1 was selected to reflect the water-sealed safety of the operating project. Based on Fig. 17, it could be found that the vertical water curtain system could raise the lowest groundwater at the separation distance of 80 m to that of 200 m without the vertical water curtain system. Thus, in some conditions with site constraints, smaller separation distances could be adapted with a vertical water curtain.

3) The layout of the vertical water curtain system should also be depended on the surrounding rock and fracture distribution of the operating project. In addition, some advanced techniques (e.g. drilling process monitoring and borehole televiewer) could be used in the investigation boreholes and vertical water curtain boreholes. Interesting and useful information regarding the spatial distribution of rock could be reflected (e.g. a negative exponent attenuation law was found regarding the permeability coefficient of surrounding rock in the cavern in this study).

However, this study is associated with some limitations. In this study, the size of the model was 2200 m × 2200 m. The width and height of the cavern were 20 m and 30 m, respectively, while the diameter of the water curtain borehole was merely 100 mm. This is a multi-scale problem of a large-scale seepage field. The computational efficiency will be low if the fracture in the model is considered. The numerical model analyses in this study are based on the equivalent, continuous medium theory, and on Darcy’s law. A refined model considering the fracture distribution should be conducted in following studies. Furthermore, the model in this study was in steady state instead

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**Fig. 16.** Seepage field variation with water curtain system functioning above the proposed project.

**Fig. 17.** Lowest groundwater above cavern #1 of the operating project.
of a transient state. However, the transient state model is encouraged to be studied in the future. Additionally, the impact of the blasting effect on the safety of the operating project should also be considered. The enormous energy released by excavation blasting will cause a series of issues to the surrounding rock, such as instability, expansion of original cracks, and generation of new cracks. These issues could enlarge the permeability of the rock mass. Thus, the operating project may be exposed to a leakage risk. Thus, the blasting effect should be taken into consideration in further studies, even if it is beyond the scope of this study.

6. Conclusion

This paper describes a comprehensive study of the water-sealed safety of an operating underground crude oil storage subjected to the construction of an adjacent new cavern. The results show that for areas with good geological engineering conditions, e.g. relatively intact rock mass with no major faults, it is feasible to site the new underground water-sealed storage cavern near the operating project, with significant cost-saving benefits from their operations. Three major factors were analysed and used as indicators for the assessment of the influence of new constructions on the operation of the existing cavern. Comprehensively considering the three factors, a safe distance of 200 m was recommended between the operating and proposed project. Then, some recommendations were given for the practice, e.g. vertical water curtain could be set in some conditions with site constraints to reduce the separate distance between the two projects. The results of this study have led to a cost-effective design of underground water-sealed storage cavern system that is expected to reduce its operational cost.

Acknowledgements

This work is supported by the National Natural Science Foundation of China (No. 41572301, No. 40902086) and the Fundamental Research Funds for the Central Universities of China (No. 2-2017-089, 2018CDJSK04XK09). Thanks are due to senior engineer Zhenhua Peng and Junyan Li of Cooec-Enpal Engineering Co., Ltd. for valuable data. The authors would also like to acknowledge the anonymous reviewers for their valuable comments and suggestions, which helped to significantly improve the quality of this paper.

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