Design and operation problems related to water curtain system for underground water-sealed oil storage caverns

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Abstract

The underground water-sealed storage technique is critically important and generally accepted for the national energy strategy in China. Although several small underground water-sealed oil storage caverns have been built in China since the 1970s, there is still a lack of experience for large-volume underground storage in complicated geological conditions. The current design concept of water curtain system and the technical instruction for system operation have limitations in maintaining the stability of surrounding rock mass during the construction of the main storage caverns, as well as the long-term stability. Although several large-scale underground oil storage projects are under construction at present in China, the design concepts and construction methods, especially for the water curtain system, are mainly based on the ideal porosity medium flow theory and the experiences gained from the similar projects overseas. The storage projects currently constructed in China have the specific features such as huge scale, large depth, multiple-level arrangement, high seepage pressure, complicated geological conditions, and high in situ stresses, which are the challenging issues for the stability of the storage caverns. Based on years’ experiences obtained from the first large-scale (millions of cubic meters) underground water-sealed oil storage project in China, some design and operation problems related to water curtain system during project construction are discussed. The drawbacks and merits of the water curtain system are also presented. As an example, the conventional concept of “filling joints with water” is widely used in many cases, as a basic concept for the design of the water curtain system, but it is immature. In this paper, the advantages and disadvantages of the conventional concept are pointed out, with respect to the long-term stability as well as the safety of construction of storage caverns. Finally, new concepts and principles for design and construction of the underground water-sealed oil storage caverns are proposed.

1. Introduction

China has become the largest net importer of petroleum in the world from October 2012 onward, followed by the USA. Establishing national strategic energy reserve storage is critically important. In this circumstance, storage of energy reserve has been one of the strategic measures in relation to the economy development and security in China [Pan, 2004].

In August 2006, the first phase of the strategic petroleum reserve (SPR) project in China, i.e. Zhenhai ground reserve base, became operational. In the second phase of the SPR project in China, it is of top priority to construct the underground storage caverns. Several candidate sites have been screened, such as Huangdao in Shandong Province, Jinzhou in Liaoning Province, Zhanjiang in Guangdong Province, and Yangpu in Hainan Province. The first large-scale underground water-sealed oil storage project in China, i.e. Huangdao project, started to construct in November 2010, and was put into operation at the end of 2014 [Li et al., 2014; Wang et al., 2015]. In 2014, the third phase of the SPR project in China adopted the underground reservoirs for the storage of SPRs.

The concept of underground water-sealed oil storage cavern was pioneered in Sweden in the 1940s [Morfeldt, 1983]. After that many countries have carried out intensive studies, such as Norway (Rehbinder et al., 1998; Blindheim et al., 2004), Sweden (Sturk and Stille, 1995), Korea (Lee et al., 1996, 1997; Lee and Song, 2003), Japan (Tezuka and Seoka, 2003), and France. In order to store crude oil in underground rock caverns and to ensure the gas/oil tightness,
underground oil reserves in caverns without lining were proposed in Sweden (Morfeldt, 1983). For the purpose of maintaining a stable groundwater level to reach storage requirements using Sweden method, Professor Ingvar Janelid proposed a method using artificial water curtain, i.e. excavating water curtain tunnel in the main caverns and drilling holes for water filling on the water curtain tunnel wall. This can form a water curtain system for the main caverns to maintain a stable groundwater level for ensuring water sealing conditions. The water curtain sealing technology was then formed, which is called hydrodynamic sealing technology. The specific approach is to drill the injection holes in the rock mass at the top or in the both sides of the reservoir. Water is injected through the water curtain holes to maintain the natural groundwater level, and thus exert a required pressure above the base oil and gas pressure to ensure the gas/oil tightness of underground reservoir, as shown in Fig. 1. The storage principle and operation mode of the underground oil storage caverns are that the water infiltrating into the reservoir is collected by the water pit at the bottom of the reservoir, and then is regularly pumped out so that the oil can be stored in a large-scale underground cavern.

Although a number of studies have been conducted on underground water-sealing system (e.g. MPCI and WIG, 1977; Gao and Gu, 1997; Li et al., 2005, 2012; Wang and Yang, 2008; Shi and Liu, 2010; He, 2011), the design concept and method for large-scale underground water-sealed oil storage caverns, especially for the water curtain system, were rarely reported in China. The principle and method used in foreign cavern design may not be suitable for the projects in China. The sealing effect of the water curtain system has already been proved to be effective in practice, but the role of the water curtain system in underground oil storage caverns may be overemphasized in the period of the cavern construction. In this regard, the negative impact of the water curtain system on the stability and safety of the main caverns is ignored to some extent. Sometimes, for instance, when the surrounding rock mass is poor and the construction activities including excavation and supporting are performed in unfavorable condition, engineers on site are still asked to keep the water curtain system operation in designed high pressure. In practice, it is mandatory that the water curtain system should be set 20 m ahead of the main cavern excavation face, even though a faulted zone with serious water seepage is encountered during the main cavern excavation, and the designed pressure of the water curtain system should be kept by continuous water supply. Another problem is that the principle of “filling joints with water” is overemphasized without any further analysis, even when the fractures directly connect to the main caverns. To address these problems, the relationship between water curtain system and main storage caverns is discussed in this paper.

![Fig. 1. Operation concept of underground water-sealed oil storage in rock caverns.](image1)

![Fig. 2. Location depth of underground water-sealed oil storage cavern.](image2)
2. Key design issues of water curtain system

For an underground oil storage cavern associated with water curtain system, the key design basically covers the following three issues.

(1) Necessity of water curtain system

The hydrogeological conditions are critically important in design of an underground oil storage cavern. Thus, hydrogeological information, such as the weather condition, rainfall, groundwater level distribution, water conservation, permeability of overburden, and penetrability of surrounding rocks of storage caverns, should be understood prior to construction. To better understand the behavior of underground oil storage caverns, numerical analysis can be conducted using above parameters as well as oil/gas pressure in storage caverns, so as to observe groundwater level change after construction and the lowest water level during operation, \( D_{lw} \).

In case of nature hydrological condition, if the lowest groundwater level above the caverns cannot meet the requirements of designed water level \( D_{bw} \), as given in Eq. (1), the water curtain system must be used (Fig. 2):

\[
D_{lw} \geq D_{bw} = D_{Em} + H_{Eq} + H_{sa}
\]

where \( D_{Em} \) is the embedded depth above the cavern roof; \( H_{Eq} \) is the equivalent water head of the gas pressure; \( H_{sa} \) is the safety water head, normally \( H_{sa} = 15 \) m is considered in practice.

In addition, increasing the overburden depth of oil storage caverns can be considered. The changes of technical and economic indices should be balanced.

(2) Working pressure of water curtain system

During design of underground oil storage caverns, the position of the water curtain tunnels, and elevation and pore pressure of water curtain holes should be first determined. The length of the water curtain hole depends on the size and coverage requirements of the main caverns. The length of water curtain hole is roughly 10 m longer than the size of the storage caverns. The diameter of the water curtain hole is 100 mm and the cross-sectional area of water curtain tunnel is approximately 5 m \( \times \) 4 m (height \( \times \) span). The pressure in the water curtain hole, \( P_{wet} \), is dependent on the elevation of underground storage caverns, oil and gas pressure in caverns, field groundwater level, water head, etc. (Fig. 2):

\[
P_{wet} \geq D_{Em} + H_{Eq} + H_{sa} - D_{lw}
\]

It is clear that issues (1) and (2) are the basic principles of the water curtain system design, and can be decided accurately after investigation on hydrogeological engineering aspects of the project area.

(3) Layout and arrangement of water curtain holes

Many parameters need to be decided before construction. For this purpose, detailed and accurate information is necessary, but it is almost impossible to do so before the cavern is excavated. To facilitate the design of water curtain system, numerical modeling has been adopted in most cases. Both the analytical calculation and numerical simulation (i.e. the finite element method and the finite difference method (e.g. FLAC3D)) are based on the theory of homogeneous porous media. However, for the underground oil storage caverns in China, the geological layers are mostly composed of granite, in which seepage is significantly different from that in homogeneous porous media. In this circumstance, the permeability environments of storage caverns are difficult to be described truly. Therefore, the empirical or semi-empirical design methods are commonly used for the water curtain system design. For example, the clear spacing between water curtain holes is generally governed by the penetrability of surrounding rocks, and the length of 10 m clear spacing is generally used (Table 1).

3. Problems of water curtain system

3.1. Effect of water curtain system on stability of oil storage caverns

(1) Engineering example

It is well known that the effect of water curtain system on gas/oil tightness of oil storage caverns has been proven. However, too much emphasis on the effect of water curtain system will induce potential limitations. In Huangdao project, at chainage 0 + 456–0 + 475 of the main cavern No. 5, the elevation ranges from \(-29.5\) m to \(-46\) m, and poor geological conditions were observed on the left sidewall. There were intensively fractured zones with large water seepage, which was a great disadvantage to the stability and construction safety of the main cavern. In order to maintain the original groundwater level with respect to water loss as required in the Code GB 50996-2014 (2014), water had to be injected to the surrounding rocks through water curtain holes during cavern construction. This, unexpectedly, resulted in a large-scale collapse in tunnel section under unfavorable geological condition (Fig. 3).

It is shown that the water curtain system has a positive role in sealing fractured rocks, but also a negative effect on the stability of caverns. The long-term water seepage of water curtain system is likely to take place at the top of the cavern, as water infiltration gradient to the inside can form excessive load applied to surrounding rocks of the caverns, which will also impose a serious problem on rock strength weakening. Block analysis results show that block safety factor decreases sharply after the excavation of cavern in the presence of seepage pressure, and the number of unstable blocks also increases (He, 2011).

(2) Relation between main cavern construction and water curtain system operation

It is recognized that the stability of caverns and gas/oil tightness are the fundamental issues for the success of underground water-sealed caverns. One can see from the literature that oil and gas can be successfully stored underground without water curtain in a favorable geological condition, such as intact rock (e.g. salt rock), using full-section concrete lining, high-quality backfill grouting, and consolidation grouting. But in poor geological condition (e.g. water-rich condition), it may not work when using the water curtain system. In this case, too much water flows into the cavern. For the storage project near the sea, sea water can be used and a large amount of water can be injected to maintain the sealing water head while maintaining the volume of the tank. But the operation cost will be increased sharply. The fresh water used in the water curtain system will be polluted, and sewage treatment is also costly. China has been facing increasingly severe water scarcity, therefore the long-term cost of water resources must be considered when using water curtain system method.

During construction of the oil storage project, the water curtain system operation should not impose damages to the stability of surrounding rocks of the main cavern. This should also be an important principle for the water curtain system during cavern construction. However, in the related design specifications in China,
it is required that water curtain system must be set at least 20 m ahead of the excavation face of main cavern, to maintain a constant pressure during water injection. This is not suitable for all geological conditions of rock mass, and thus should be modified.

3.2. Water curtain system operation and loss of groundwater level during cavern construction

Taking a project in China for example, the underground water-sealed oil storage caverns under construction have a volume of $3 \times 10^6$ m$^3$, which consist of four tanks. Each tank is composed of two caverns: 24 m in height, and 19 m in span. The water curtain tunnel is parallel to the main cavern, and arranged 25 m above the cavern. There are five water curtain tunnels, with cross-sectional area of 6.5 m$^2$ x 6 m. The water curtain hole is 60 m in length and 100 mm in diameter. The spacing between horizontal holes is 10 m, and that between vertical holes is 20 m.

The guideline of this project mentioned that: “In order to ensure the water sealing effect of the caverns in the entire life cycle, special attention should be given during the construction period. If excessive loss of groundwater is observed during construction, it may lead to the failure of the whole project.” (Wu, 2011). In this regard, many scholars believed that the loss of groundwater level in construction may lead to failure of this project, a hot topic to be discussed herein.

The first issue is that some scholars considered the water sealing effect as the decisive factor that makes underground cavern construction successful. However, it may be incorrect from the experiences of the Huangdao project. As mentioned earlier, the

<table>
<thead>
<tr>
<th>Project name</th>
<th>Stored item</th>
<th>Volume ($10^6$ m$^3$)</th>
<th>Rock type</th>
<th>Parameters of water curtain holes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perama, Greece</td>
<td>Gasoline and crude oil</td>
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<td>Limestone</td>
<td>Clear spacing (m) 20</td>
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<td>Diorite</td>
<td>7, 14</td>
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<td>10</td>
</tr>
<tr>
<td>Jurong-I, Singapore</td>
<td>Crude oil and other hydrocarbons</td>
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<td>Volcanic, sedimentary rock</td>
<td>10 (measured from figure)</td>
</tr>
</tbody>
</table>

Fig. 3. Collapse of sidewall in main cavern No. 5 (local).

Fig. 4. Groundwater level curves of piezometric holes ZK003 and ZK004.
It is mentioned earlier that most of the China's underground oil storage caverns are constructed in granite of good quality. The seepage characteristics of fractured rock mass in the water curtain system are difficult to explain by using uniform medium seepage model. Unfortunately, some design concepts and principles of water curtain system for fractured rocks are always using the concept of “filling joints with water” (Li et al., 2015).

4. Concept of “filling joints with water”

In many cases, the “filling joints with water” is defined as a concept of the water curtain system designed for some engineers involved in the Huangdao project. However, Yuan et al. (2006) mentioned that from the perspective of the underground oil storage, the groundwater is not prerequisite. It is an essential factor only when open fractures appear in the rock mass. The fractures and the groundwater present a relationship of “filling joints with water”. This relationship undoubtedly exists in non-absolutely closed fracture below the groundwater level. However, in practice, the “filling joints with water” concept often interprets that as long as the crack exists, it is mandatory to artificially use water to fill. A question arises: Is it necessary to always fill joints with water? To fully understand this concept, the situation of the “joints” should be first investigated, and then a suitable measure can be taken. There are three cases as follows:

![Fig. 5. Initial groundwater level contours before project construction. All values are in meter.](image-url)
(1) Case 1: The fractures connect to the main cavern, but the opening of the fracture is not such large. If the fracture is filled with water through the water curtain system, only wet surface and no seepage-induced cracks will be caused, and the overall stability of cavern is still maintained. In this case, no special measure needs to be taken except the water curtain.

(2) Case 2: In the case that large fractures directly connect the main cavern to artificial water systems (such as water curtain holes and water curtain galleries), hydrological exploration holes, or piezometric holes, a continuous flow passage is formed, then grouting and plugging should be used for blocking the passage, i.e. using “grouting” instead of “injecting water”.

(3) Case 3: The fracture opening scale is modest, and the fractures are intensively developed in the rock mass. Consolidation grouting treatment and poor material replacement should be implemented due to softening of weak layers in the fractures, considering the long-term stability of the underground structure.

Using the measure of water supply or grouting depends on a variety of factors, such as site-specific hydrogeological conditions, water resources, long-term operation mode, total cost, and environmental protection. The practicable control system standards should be proposed according to field conditions, rather than directly using water supply.

4.2. Application condition of “filling joints with water” concept

It is widely acknowledged that if the joints of case 2 are observed in the main cavern during construction, the pre- and post-grouting measures should be adopted. But at the beginning of main cavern excavation of Huangdao project, if the joints are observed in water curtain system, especially in water curtain holes, the grouting measure will not be allowed to use; even if no pressure is imposed on those water curtain holes, water from the holes can access into the main cavern.

Some people believe that grouting in water holes will violate the rule of “filling joints with water” and damage the water curtain system. In fact, this concept has not been proven experimentally. In Huangdao project, there were several holes in water curtain tunnel No. 3. These holes connect to the main cavern No. 8 through fractures or joints. The pressure in these holes were always zero, even though a large amount of water was injected during the hydrodynamic test, resulting in a serious leakage of the main cavern No. 8 near chainage 0 + 500. In this regard, repeated grouting at that position was not effective. To effectively reduce leakage, direct grouting in the water curtain hole in water curtain tunnel No. 3 was finally implemented. The tightness test of the whole cavern showed that the severe leakage was reduced, and no negative effect was produced on sealing performance of the water curtain system. It was indicated that the measure of “filling joints with water” is not always necessary.

5. Grouting problems related to water curtain system

To decrease the water leakage to the main caverns, the pre- and post-grouting measures are required during the excavation. But there are some problems related to grouting needed to be considered when the water curtain system is operational.

5.1. Effect of grouting in caverns when water curtain system is working

Engineering experiences show that the post-grouting of the main storage cavern is time-consuming, and the grouting has its limitation in leakage control when the water curtain system is operational. A main cavern with serious leakage in Huangdao project was repeatedly grouted at the same position for five or six times, but the grouting effect was not obvious as expected. The reasons may be considered as follows:

(1) In the main storage cavern, the leakage area is significantly increased as a result of fracture initiation and propagation induced by blasting.

(2) Low-pressure post-grouting of surrounding rocks in shallow layer has small diffusion range.

(3) The leakage position cannot be accurately located due to the presence of shotcrete.
(4) Pressure gradient of grouting slurry in surrounding rocks is in the opposite direction to the hydraulic gradient of water curtain system, which can prevent slurry diffusion and carry away cement particles that are not solidified, resulting in reduction of grouting effect.

The pre-grouting also has the following defects:

(1) Advanced geological forecast is needed before pre-grouting.
(2) In high in situ stress condition, fractures in rocks are basically closed. In this circumstance, low-pressure grouting is not suitable. When blasting is used for excavation, fractures will re-open, which may reduce the pre-grouting effect.
(3) Additional time of slurry solidification is needed for pre-grouting, thus rock mass cannot immediately be excavated using blasting method, which can delay the construction schedule.

From the experiences of Huangdao project, it is shown that water curtain hole can offer detailed geological information of rocks, which is helpful for grouting.

5.2. Blocking water passages using information of water curtain holes

The water curtain holes are basically set overlying or in the vicinity of underground oil storage cavern, with spacing of 10 m and length of tens to more than one hundred meters. These water curtain holes are helpful in investigating geological structures, seepage characteristics, and distribution of groundwater near the underground storage cavern by using the pressure distribution figure of water curtain holes (Fig. 7).

Fig. 7 is plotted by recording the water pressure in each water curtain hole during the water injection of the hydrodynamic test for the whole system. The abscissa shows the location of the water curtain hole with identifier, and the ordinate is the pressure value of each hole.

Once the following situations are observed in water curtain hole, such hole must be grouted immediately: (i) the water pressure in the hole is zero or significantly lower than the designed pressure, or (ii) the water supply volume is much larger than the average water flow volume of water curtain.

In addition, three-dimensional imaging observation in the holes may be conducted to accurately locate the position of the joints, fissures, and fractured zones. The grouting with double-plug method in the corresponding position of a hole can then be implemented. This grouting method is used to effectively seal the leakage passage to the main cavern, and high grouting pressure can be used without any damage to the surrounding rocks of the cavern. The seepage is conducive to the spread of the slurry to the rock mass below the water curtain system, and has less negative effect on the water curtain system.

It is revealed from the engineering practices of Huangdao project that, the number of water curtain holes to expose large joints or centralized seepage channels is less. There are more than 500 water curtain holes in this project. Nineteen of them (4%) cannot reach the required pressure, and three holes (0.6%) do not need to be pressurized. It is clear that only plugging and grouting several water curtain holes will not damage the water curtain system.

On the other hand, only when the seepage passage connecting to the main cavern is completely blocked, water from water curtain system can then fill the distributed fractures surrounding the caverns, and raise the groundwater level to meet the hydrodynamic potential energy requirement for gas/oil tightness.

6. Conclusions

In the first large-scale underground water-sealed oil storage cavern in China, several design and operation concepts, related to water curtain system of underground oil storage cavern in fractured rocks, are proposed. The following conclusions can be drawn:

(1) The water curtain system is a conventional approach, but its parameters cannot be accurately determined. Only an approximate range of values can be estimated. There is an adjustment possibility for water curtain system in the construction process. The water curtain system should be adequately used by considering the stability of surrounding rocks of storage cavern.
(2) The stability and sealing performance of the main cavern are the fundamental conditions for safety operation. The water curtain system is a dominant factor for the main cavern sealing, but is always a negative factor for the stability of the cavern.

(3) It has been proved by several engineering examples that the water curtain system can be successfully built after completion of underground caverns, even though the geological condition is unfavorable.

(4) The numerical results obtained by the continuous porous media theory can be used for comparative analysis of water curtain system. The so-called viewpoint “water curtain system must be set at least 20 m ahead of the main cavern excavation face, and a constant pressure of water injection operation should be maintained” is lack of theoretical and practical basis during the construction of underground water-sealed caverns in fractured rocks. It is also not suitable for the rock mass with poor geological condition.

(5) The concept of “filling joints with water” mainly refers to as the relation between joints and groundwater. The concept has been accepted by many engineers in the field of oil storage engineering. However, it is not always correct. Sometimes, it may be better to treat joints using grouting instead of filling with water, because the water will cause serious seepage, leading to the instability of the main caverns. If the joints connect the main caverns to water curtain holes, or other geological exploration boreholes, the grouting must be performed.

Conflict of interest

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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