Discussion on the optimal spacing of water curtain holes in cavern reservoir

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Abstract Vertical and horizontal water curtain holes can be effectively used to seal underground oil storage caverns. However, the density of hole spacing affects the water sealing effect of the water curtain system. Based on the basic theory of Darcy’s law, this study established a three-dimensional model involving a main oil storage cavern, water curtain tunnel, water curtain hole, and surrounding rock mass. Different seepage effects on water curtain holes under different spacing are calculated and analyzed using a numerical analysis method. The optimal water curtain hole layout is finally determined by comparing the recommended spacing with the minimum water head difference.

KEYWORDS Underground oil reservoir, Seepage law, Water curtain hole, Spacing optimization, FEM

1. Introduction
The water curtain system includes a water curtain hole and tunnel to ensure a stable groundwater level over a long period. The design technology involves some initial parameters such as the permeability of rock mass and water level difference to determine the water sealing effect of the oil storage cavern. Water curtain holes are arranged to realize the water sealing effect of the lower main oil storage cavern to achieve the good circulation of water surrounding the oil storage cavern [1]. The water curtain hole usually employs Φ 100 mm–Φ 150 mm vertical and horizontal drilling. Due to the small-diameter holes and low rock mass permeability, it is necessary to increase the density of drilling holes to achieve tight sealing; however, this will increase the drilling cost.

This study discusses the optimal spacing of water curtain holes, determined by numerical analysis on conditions of low rock permeability.

2. Principle
Based on the basic principle of sealed theory, the pressure of fracture water of the surrounding rock must be greater than the oil cavern [2]. However, the oil cavern is filled by the mixture of oil and gas. In order to seal the oil and gas in the cavern, the operating pressure, i.e. the pressure in the oil cavern, usually keeps blowing 0.2MPa for a safety operation.

The pressure difference between the water and operating pressures creates a constant water head difference. Thus the seepage water will penetrate every surface of the rock mass in the oil storage depot at a very low flow rate to prevent oil leakage. Meanwhile, the seepage water at the cavern bottom will regularly accumulate to form a water cushion.
Many research on rock mass seepage are generally based on two theories. One such theory is the Darcy’s law used in classical soil mechanics, where the seepage law of the soil is also applicable to rock mass [3–4]. Another theory is that underground seepage water in the rock mass is permeated from joints and fracture surfaces between rock bodies, and the velocity is much greater than that of the flow through the bulk of the rock mass. Based on the second theory, the double medium seepage model is established.

Objectively, the double medium seepage theory is more reasonable than the classical soil mechanics seepage law for crud rock mass. However, technically, the distribution of all joints and fractures in the rock mass cannot be fully elucidated, leading to input uncertainties [5]. Therefore, the classical Darcy’s law is widely used in most seepage software (FEFLOW, PLAXIS, ANSYS, etc.). In this study, ANSYS software is used to compute the seepage field, and the calculation principle is also based on the classic Darcy’s law.

![Figure 1. Seepage principle of oil storage](image)

3. Modals

According to one preliminary design document of an oil storage cavern, a three-dimensional model of the rock and water curtain system is established, and the rock mass parameters are determined.

3.1. Oil storage cavern and water curtain tunnel

![Figure 2. Section shapes of oil cavern and water curtain tunnel](image)

The dimensions of the oil storage cavern are 934 m × 19 m × 24 m for the length, span, and height, respectively. The cavern tunnel type adopts three center arch straight-walls, and the bottom is properly cut angle. The design section area is 436.1 m². During the operation period, the tunnel bottom was a 500 mm thick water cushion, with an area of 8.6 m². Excluding other areas, the tunnel’s effective oil storage area is 414.3 m².
The length of the water curtain tunnel is 974 m, and the section is 6.5 m × 6 m. The tunnel comprises a straight wall with three center arches. All the five curtain tunnels’ extension direction is coaxial with the oil storage cavern. They are located at the upper part of both sides of the main cavern. The horizontal and vertical water curtain holes are drilled at the sidewall and the bottom of the curtain tunnel. All these tunnels and holes together constitute the extensive water curtain system.

3.2. General layout relationship

The surface elevation of the bottom of the water curtain tunnel is between −32 m and −34 m. The roof elevation of the main oil storage cavern is −56 m. Therefore, the height difference from the roof to the water curtain bottom is between 22 m to 24 m, as shown in Figure 3.

All the water curtain holes are continuously injected water around the main caverns to strengthen the water seal effect, as shown in Figure 3. According to the design documents, the horizontal and vertical water curtain systems comprise tunnels and holes. The diameter, horizontal and vertical spacing of the water curtain holes are 100 mm, 10 m, and 20 m, respectively.

The drilling direction of the water curtain hole is vertical to the main oil storage cavern. The horizontal water curtain above covers all the oil storage caverns, and the length of the water curtain hole is 55–65 m. The vertical water curtain holes are 20 m longer than the extension of the oil storage cavern in the axial direction. The holes’ upper end is at the same level as the water curtain tunnel’s bottom, and the lower end extends 10 m lower than the oil cavern’s bottom.

3.3. Model

This study employed a pair of oil storage caverns as the research unit for the convenience of calculation. First, we establish a three-dimensional model to simulate the seepage relationship between the water curtain system and oil caverns. As shown in Figure 4, the curtain tunnel forms a hydraulic circle on the upper and surrounding sides of the oil storage cavern through the 100 mm diameter water curtain holes.
4. Seepage parameters and boundary conditions

4.1. Seepage parameters
The permeability of the dense rock is much lower than that of the soil layer. There is no absolutely impermeable rock. The permeability coefficient is equal to the seepage velocity when the hydraulic gradient is 1. For an unfractured rock with no dissolution, the permeability coefficient depends on the rock's primary structure. The rock mass's integrity is good for a slightly weathered granite below 80 m underground site. In site, the rock mass's permeability coefficient was determined as $5 \times 10^{-8}$ m/s.

4.2. Boundary condition
The following assumptions were made in developing the finite element model.
1) The water seepages in the main oil caverns are provided by the surrounding water curtain holes, regardless of the upper aquifer above.
2) The surrounding boundary's flow is 0, meaning there is no water exchange between the surrounding rock and caverns.
3) The water level elevation is +10m, including water curtain tunnels and holes.
4) The oil cavern tunnel wall is surrounded by a free seepage surface, but for the large shape of the oil cavern, the water level elevation of the archtop is −56 m, and the bottom of the cavern is −80 m.

5. Calculation result

5.1. Observation angle
Spacing water curtain holes dramatically affects the distribution of seepage water in the rock mass, especially for the oil cavern tunnels. In this study, two different working conditions of water curtain hole spacing $D_1 = 10$ m and $D_2 = 20$ m are used to illustrate this difference. Based on design documents, the water head differences of water supply elevation is no more than 4 m. To analyze the calculation results clearly, the rock mass blocking sight was hidden, and the seepage distribution is observed and compared from three angles (shown Figure 5~7).

1) From the front, the seepage distribution of vertical water curtain tunnels and holes are shown.
2) The seepage distribution of horizontal water curtain holes and rock mass is shown from the top.
3) The seepage distribution of the right water curtain tunnels and holes is shown from the right.
5.2. Seepage distribution of $D1=10m$

Figure 5. Distribution of water head and seepage in view of from the front

Figure 6. Distribution of water head and seepage in view of from the top

Figure 7. Distribution of water head and seepage in view of from the right side
5.3. Seepage distribution of D2=20m

Figure 8. Distribution of water head and seepage in view of from the front

Figure 9. Distribution of water head and seepage in view of from the top

Figure 10. Distribution of water head and seepage in view of from the right side
6. Conclusion
The following conclusions can be drawn by comparing the head pressure and seepage distributions when considering different water curtain hole spacing.

1) When considering $D_1 = 10$ m, the water pressure distribution and seepage velocity are relatively uniform along the tunnel axis, and the maximum head pressure difference on the same horizontal plane (bottom of water curtain roadway) is 2 m. This proper spacing can ensure a good water sealing effect to oil caverns.

2) When considering $D_2 = 20$ m, the water head pressure and seepage velocity of water curtain holes are quite different in the Z direction (along the tunnel axis). The head pressure and seepage velocity is not uniform, especially in different Z directions. The maximum water head difference is higher than 20 m, greater than the allowable head difference value (4 m).

3) The function of the vertical water curtain holes is to isolate the different caverns. Although the water head pressure is small (less than the maximum water head pressure of about 20 m), it is still higher than the main cavern's water head of 30 m. Therefore, appropriate reduction of holes spacing is beneficial for economic viability.

4) The function of the horizontal water curtain holes is to ensure no oil leakage, which is crucial. Hence, we recommend spacing the tight holes with $D_1 = 10$ m for vertical water curtain hole spacing.

Based on Darcy's law, this paper analyzes the seepage distribution around oil caverns through the numerical analysis method. The results showed that the spacing of various water curtain holes influences the water sealing effect. This method is suitable for underground oil storage and LPG storage projects. It provides an effective way for determining the reasonable spacing in case of vertical and horizontal water curtain holes in underground oil storages.

REFERENCES
1. Shi Hongbin. Analysis and evaluation of water seal condition and surrounding rock stability for Huangdao water sealed underground petroleum storage caverns in rock [D]. Beijing Jiaotong University Doctoral Dissertation, 2010. 06.
2. Liang Bin. Seepage simulation and Evaluation of water sealed effect of Zhanjiang Underground Petroleum Storage Cavern [D]. Master's thesis of China University of Geosciences, 2011, 05.
3. Zhang Qi-hua, Some Ideas on Assessment and Control of Water Tightness Effect in Huangdao Oil Storage Cavern. [J]. Journal of Yangtze River Scientific Research Institute, 2014, 31(8). pp 112-116.
4. Guiwu Han, Moupeng Hu, Yin Li. Effects of Tunnel Shape on Water Sealed Oil Storage Caverns Seepage Flow [M]. ICPTT 2014. pp178-195.
5. Qi-Hua Zhang, Jian-Min Yin. Solution of two key issues in arbitrary three-dimensional discrete fracture network flow models [J]. Journal of Hydrology 514 (2014) 281–296. pp281-296.