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Review

Advances in water sealing mechanisms and technologies for underground oil storage caverns

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Abstract: Deep underground energy storage is crucial for efficient energy utilization, strategic petroleum reserves, and overall energy security. This paper provides a systematic review of the theoretical and technological advances in water sealing control for underground oil storage caverns, drawing on extensive literature and field practice. The discussion focuses on sealing effectiveness criteria and seepage analysis, with particular emphasis on the water curtain system as the core mechanism for maintaining hydraulic integrity. Numerical simulations and long-term field monitoring are highlighted as key tools for evaluating seepage behaviour and guiding design and operation. Water sealing control mainly targets concentrated seepage zones and water pressure failure areas through water plugging and targeted recharge. Typical engineering measures include optimizing water curtain parameters, implementing precise grouting to reduce seepage in storage zones, and reinforcing the surrounding rock with anti-seepage supports. The ultimate objective is to minimise water loss while ensuring a stable and reliable hydraulic seal. In addition, the review analyses the role of hydraulic gradients in controlling sealing performance and outlines future research priorities aimed at enhancing the long-term reliability, safety, and economic efficiency of water sealing technologies for underground oil storage caverns.

Keywords: Water sealing cavern; water sealing theory; air tightness criterion; water sealing control

1. Introduction

Energy is a fundamental driver of economic growth, social development, and technological progress. In the context of rapidly increasing global energy demand and the escalating threat of climate change, the decarbonization and clean transformation of energy systems have become urgent priorities for the mitigation of global warming (Liu et al., 2023; Zhang et al., 2025; Chang et al., 2025). Large-scale, high-efficiency energy storage technologies are crucial for achieving these objectives, particularly in addressing the key technical challenges associated with deep underground energy storage (Yang et al., 2023). The petroleum industry in China has developed rapidly, and its strategic role within the national energy framework continues to strengthen. However, domestic oil resources remain limited, and the dependence on foreign oil has exceeded 73%. According to the requirements of the International Energy Agency, each member state must maintain an emergency oil reserve equivalent to at least 90 days of net imports from the previous year (Shi et al., 2023). On this basis, China should maintain more than 180 million tonnes of oil reserves by 2024, corresponding to a storage capacity of no less than 210 million cubic meters. In practice, a substantial gap remains in the strategic oil reserves of China, which highlights the urgent need to accelerate the construction of large-scale energy storage facilities (Pan, 1996).

Oil storage methods can generally be divided into above-ground and underground systems. Above-ground storage commonly relies on large steel tanks, whereas underground storage includes artificial salt caverns, abandoned mines retrofitted with water curtain systems,

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unlined underground rock caverns, geologically suitable aquifers, and depleted oil and gas reservoirs (Wang and Yang, 2008). Among these options, underground oil storage caverns are widely regarded as one of the most effective and secure solutions for large-scale storage of crude oil and refined petroleum products. They offer several advantages, including high intrinsic safety, favourable economics, limited land occupation, long service life, and strong suitability for strategic and emergency applications (Yang, 2005; Ma, 2015; Wang et al., 2022). Nevertheless, engineering practice has revealed a series of design and operational challenges associated with water curtain systems, suggesting that traditional design concepts, such as simply "filling joints with water," are not sufficient to guarantee long-term hydraulic containment under complex geological and hydrogeological conditions (Li et al., 2016a).

Underground oil storage caverns have been developed for more than 80 years and are now widely adopted by major oil-reserve-holding countries such as Sweden, Finland, Japan, South Korea, India, and Singapore (Xu, 2010). The technology originated in the 1930s, when Sweden first applied for a patent for unlined underground oil storage caverns (Morfeldt, 1983), and was successfully implemented in Stockholm in the 1950s. The 1970s then marked a phase of rapid global expansion, during which millions of cubic metres of underground storage capacity were constructed annually (Liu et al., 2008). In parallel, the theoretical framework for unlined underground caverns, particularly with respect to water sealing control, was systematically developed and refined (Åberg, 1978a, 1978b; Suh et al., 1987; Rehbinder et al., 1988). Subsequent studies proposed integrated empirical, numerical, and experimental approaches for assessing the containment properties of water-sealed caverns and demonstrated their effectiveness in representative pilot projects (Qiao et al., 2017). Between 1987 and 1992, Japan constructed approximately 5 million cubic metres of underground oil storage capacity in Kuji, Kikuma, and Stringwood Wild. In the early twenty-first century, South Korea added a further 18.3 million cubic metres of capacity (Du et al., 2006). India then developed about 6 million cubic metres of underground oil storage facilities between 2008 and 2014 (Sigl et al., 2014; Usmani et al., 2015), and Singapore built 4 million cubic metres of storage on Jurong Island between 2014 and 2016 (Winn, 2020). For coastal and island storage bases, seawater intrusion and salinization introduce additional challenges to the long-term performance of water-sealed systems, and targeted prevention technologies have therefore been developed and applied in large-span underground caverns (He et al., 2023).

Although the construction of underground oil storage caverns in China began relatively late, their development has accelerated markedly in the 21st century. In the 1970s, underground caverns with capacities of 40,000 and 150,000 cubic metres were constructed in Xiangshan, Zhejiang Province, and Qingdao, Shandong Province, respectively, for the storage of refined oil products and crude oil (He, 2007). Entering the 21st century, China initially built 3 million cubic metres of underground oil storage capacity (Hong, 2014), followed by the construction of several large-scale facilities with capacities reaching up to 5 million cubic metres. In recent years, an increasing number of commercial enterprises and energy corporations have adopted, or plan to adopt, underground oil storage caverns as a key component of their energy infrastructure (Liu et al., 2022).

The theory and technology of water sealing control are key determinants of the success or failure of large-scale underground oil storage cavern projects. Building on published research and engineering practice, this study reviews recent advances in water sealing theory and control technologies, and integrates field experience to provide comprehensive insights and practical guidance for the design, operation, and long-term regulation of underground oil storage caverns.

2. Design and construction principles for the water sealing function of underground oil storage caverns

2.1. Introduction to underground works of water sealing oil storage caverns

Fig. 1 shows the three-dimensional layout of the underground works of a water-sealed oil storage cavern. The underground complex consists of several main components, including oil storage chambers, construction and access tunnels, water-sealing (water curtain) tunnels, shafts, and sealing plugs. The oil storage chambers form the primary storage space and are typically arranged as two or three parallel caverns. During construction, tunnels are designed to satisfy the requirements for ventilation, water and power supply, drainage, and the transportation of equipment and personnel. The shafts are used for ventilation and smoke extraction during construction, and subsequently provide vertical connections between the underground chambers and surface facilities during operation and maintenance. The water-sealing system controls the groundwater level through artificial recharge, thereby establishing a stable hydraulic barrier around the caverns. Sealing plugs hydraulically isolate the water-injection zone of the water curtain system from the oil storage zone, ensuring effective water sealing and safe operation of the facility.

2.2. Water sealing effectiveness design and construction principles

Fig. 2 shows the design and construction principles for achieving effective water sealing control (Kurose et al., 2014a; Aoki, 2023). The main requirements are as follows: (i) construction roadways and water-sealing (water curtain) roadways are excavated in parallel; (ii) drilling of water-sealing boreholes and initial artificial recharge must be completed before excavation of the oil storage caverns; (iii) during cavern excavation, if pore water pressure or seepage conditions in the storage area do not satisfy the design requirements, additional water sealing control measures should be implemented in a timely manner; (iv) anti-cracking measures are applied during the pouring and curing of sealing concrete to ensure structural integrity (Li et al., 2012); and (v) gas tightness tests are conducted to verify that the pressure drop of inert gas remains within the specified allowable range.

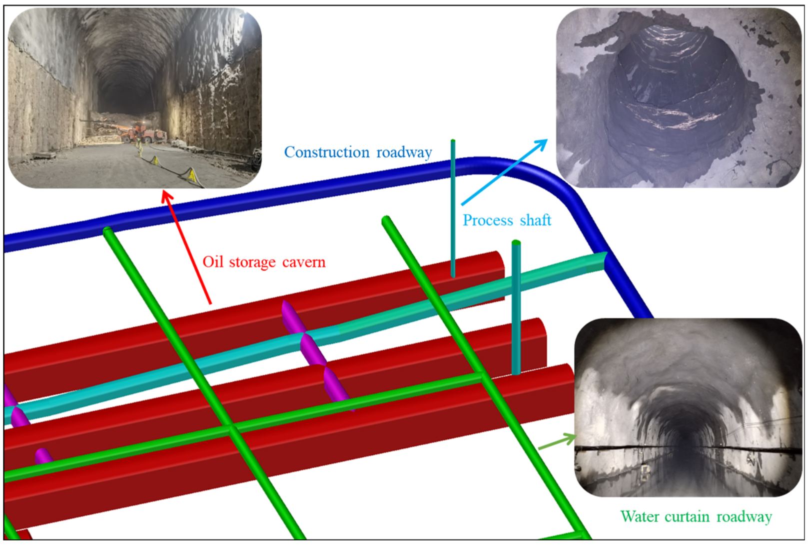

Fig. 1. 3D schematic diagram of underground engineering of water sealing caverns.

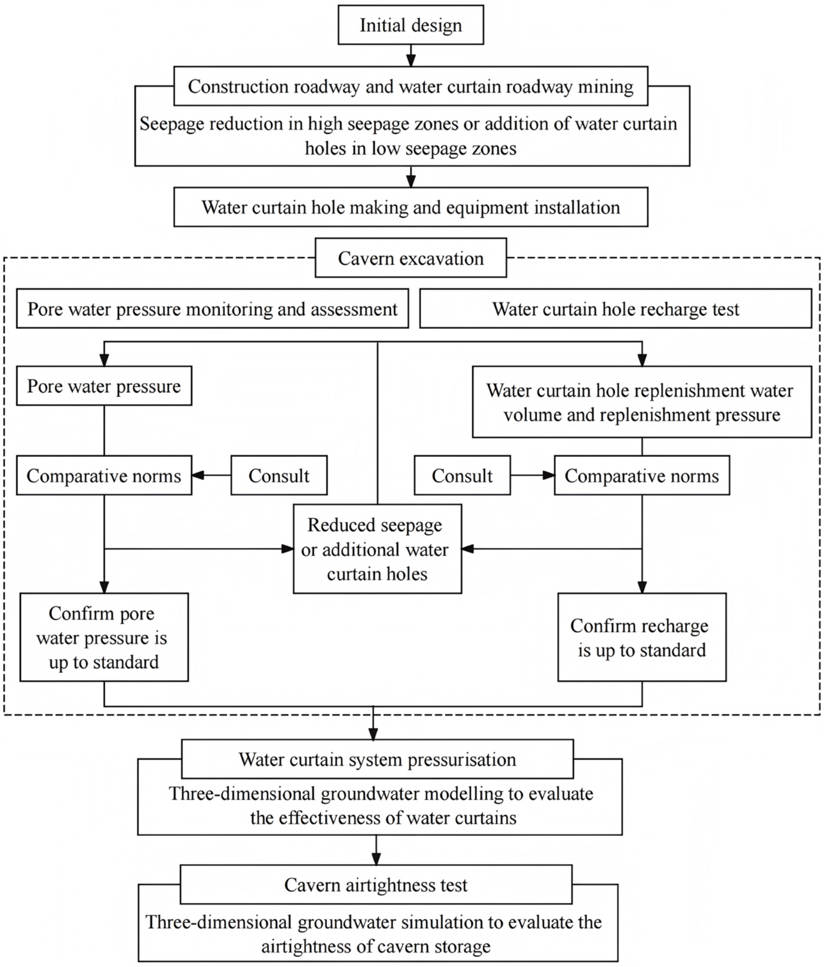

Fig. 2. Design and construction principles of water-sealed system. (Redrawn from Kurose et al. (2014a))

Code for Construction and Acceptance of Underground Oil Storage in Rock Caverns by Groundwater specifies that the advance length of the working face for overbreak excavation associated with the water sealing control system should not be less than 20 m (China Sinopec., 2014). To further account for the range of advance water probing and to ensure full saturation of water-conducting joints, Indian construction practice recommends that the water-filled section of water sealing control boreholes should extend approximately 40~50 m beyond the excavation face (Naithani, 2012). This comparison indicates that, in practical design, both regulatory requirements and empirical experience are used jointly to determine a reasonable advance length for water sealing control.

3. Theory of water seal regulation in underground cavern oil reservoirs

Water sealing control relies on both natural groundwater and artificial regulation. Excavation of the cavern lowers the natural groundwater level and forms a drawdown funnel. To prevent the escape of oil and gas under these conditions, artificial water replenishment is applied to restore and maintain an appropriate groundwater level. The theoretical basis of water sealing control is therefore rooted in two key aspects: effectiveness criteria for hydraulic sealing and seepage analysis of the surrounding rock mass (Zhang et al., 2018).

3.1. Water sealing effectiveness criteria

3.1.1. Critical water level criteria

Theoretically, leakage of oil and gas can be prevented as long as the pore water pressure in the surrounding rock exceeds the storage pressure within the cavern (Li et al., 2005; Goodall et al., 1988). For this reason, a stable and sufficiently high groundwater level must be maintained above the cavern (Zhang et al., 2021). Before artificial water replenishment technology became mature, increasing the burial depth of the cavern was a common approach to extend the seepage path, enlarge the recharge zone, and sustain the groundwater level. Greater depth also improves sealing performance by utilising the confining pressure of the overburden layer (Li et al., 2017; Morfeldt, 1983; Li et al., 2023). On this basis, Swedish design practice in the 1980s explicitly recommended that the burial depth of gas storage caverns should not be less than 100 m (Morfeldt, 1983).

Fig. 3 shows the critical groundwater level analysis model (Liu et al., 2022). The known groundwater level elevation is denoted as Z_2. The head loss from the groundwater level to the upper part of bubble AB is ΔH, and the total head at the upper part of bubble AB is $H_A = Z_2 - \Delta H$. The elevation of the lower part of bubble AB is Z_0, the storage pressure inside the cavern is P, the density of the bubble fluid is ρ_g, the density of groundwater is ρ_w, and the total head at the lower part of bubble AB is $H_B = \frac{P}{\rho_w g} + Z_0$. If the bubble is assumed to be in equilibrium, neglecting fluid velocity and bubble weight, the total head is given by the following Eq. (1):

$$H_A = H_B + \Delta H_f \tag{1}$$

where ΔH_f is the head loss from the top end of the bubble to the bottom end. From Eq. (1), it can be obtained:

$$Z_2 - \Delta H > \frac{P}{\rho_w g} + Z_0 \tag{2}$$

Transforming the order of the terms of Eq. (2) yields the vertical distance from the free water level to the vault of the cave:

$$H_w = Z_2 - Z_0 > \frac{P}{\rho_w g} + \Delta H \tag{3}$$

From Eq. (3), to prevent the escape of oil and gas, the vertical distance between the free water level and the vault of the cavern must exceed the sum of the stored pressure head and the total head loss of the cavern.

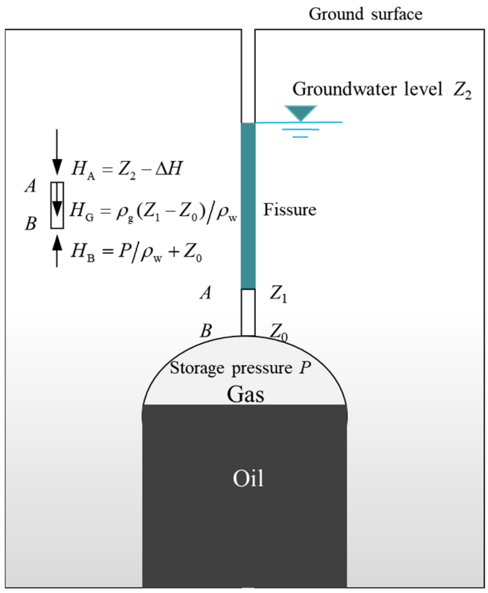

Fig. 3. Analysis model of critical water level. (Redrawn from Liu et al. (2022))

Standard for design of underground oil storage in rock caverns (China Sinopec., 2020) specifies that the vertical distance between the stable groundwater level and the cavern vault shall be no less than the value calculated according to the following formula:

$$H_w = 100P + 20 \tag{4}$$

Eq. (3) and (4) have a consistent form. The first term on the right-hand side of Eq. (4), 100P, corresponds to the storage pressure head of the cavern, while the second term, representing a 20 m head, is used to characterize the head loss. The safety margin of a 20 m head for groundwater sealing cavern reservoirs in China aligns with the safety margin provisions specified in the reservoir construction standards of Norway and India (Usmani et al., 2009; Li et al., 2017).

3.1.2. Critical hydraulic gradient criteria

In 1978, Aberg (1978b) proposed that the hydraulic gradient in the surrounding rock fissure is greater than 1, which is the necessary condition to satisfy the effectiveness of the water seal of the cave reservoir, through the analysis of the bubble force in the surrounding rock fissure. Fig. 4 for the critical hydraulic gradient analysis model, p_1 for the upper bubble pressure, p_0 for the lower bubble pressure, l for the bubble length, α for the fissure and the vertical direction of the angle, in order to ensure that the oil and gas do not escape to meet the bubble force downward:

$$p_1 - p_0 + \rho_g g \cdot l \cdot \cos\alpha > 0 \tag{5}$$

Neglecting the velocity head from the total head equality gives the following Eq. (6):

$$Z_1 + \frac{p_1}{\rho_w g} = Z_0 + \frac{p_0}{\rho_w g} + \Delta H_f \tag{6}$$

Since it can be obtained by combining Eq. (6):

$$p_1 - p_0 = \rho_w g(\Delta H_f - l\cos\alpha) \tag{7}$$

Due to the hydraulic gradient $J = \frac{\Delta H_f}{l}$, the joint Eq. (5) and Eq. (7) can be obtained:

$$J > (1 - \frac{\rho_g}{\rho_w})\cos\alpha \tag{8}$$

Since ρ_g is much smaller than ρ_w, the hydraulic gradient is approximated to satisfy $J > \cos\alpha$. When the fissure is vertical, i.e., when α =0, the hydraulic gradient must exceed 1. From Eq. (8), it can be inferred that, theoretically, as long as the hydraulic gradient in the peripheral rock of the reservoir exceeds 1, hydrocarbons will be prevented from escaping upward along the fissure. It is worth noting that the above analyses do not consider the capillary forces within the fissure and neglect the self-weight of the oil and gas, resulting in more conservative conclusions. The hydraulic gradient criterion used in a Japanese LPG reservoir is 0.5, while the actual operational hydraulic gradient exceeds 1 to ensure safety (Kurose et al., 2016).

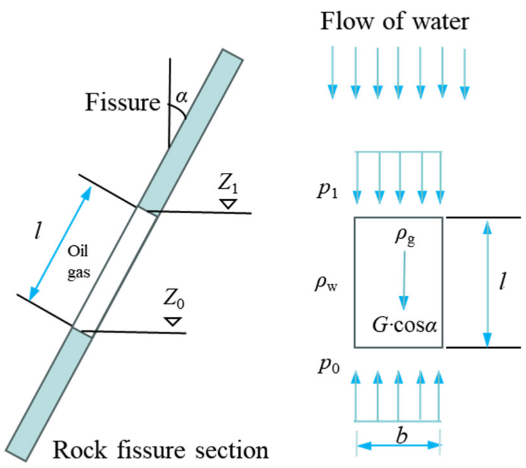

Fig. 4. Analysis model of critical hydraulic gradient.

From the principle of conservation of energy, it follows that, in the absence of a water curtain system, the average hydraulic gradient between the natural groundwater level and the cavern vault is equal to 1. Under such conditions, the hydraulic gradient cannot exceed 1 along the entire seepage path. Building on Åberg's hydraulic gradient criterion, Goodall further proposed that, to prevent gas leakage, the water pressure must increase (i.e., the hydraulic gradient must be greater than 1) over a certain distance along any potential leakage path away from the cavern (Goodall et al., 1988).

A water curtain system is therefore required to achieve effective water sealing control. Installed above the storage caverns, the water curtain system regulates the groundwater level and maintains its stability during construction, dry periods, and high-water periods. Pressurisation of the system drives artificially recharged water towards the storage area. At the same time, the additional water pressure provided by the water curtain system sustains an effective hydraulic gradient in the surrounding rock, extending from the water curtain tunnel to the cavern vault and thereby ensuring hydraulic containment.

3.2. Discussion on the mechanism of hydraulic gradient regulation on the airtightness of underground oil storage caverns

The total head can be decomposed into pressure head and elevation head. When the hydraulic gradient exceeds 1, the essential feature is that the pressure head at the upper end of a gas bubble is greater than that at the lower end. Fig. 5 illustrates the variation of pressure head under different hydraulic gradients.

When the hydraulic gradient is 0, the total head is constant in the vertical direction, and the pressure head (pore water pressure) corresponds to a purely hydrostatic state. Under these conditions, oil and gas may migrate upward under buoyancy once subjected to external disturbances. When the hydraulic gradient is 1, the slope of total head loss coincides with that of the elevation head, so the pressure head remains essentially constant with elevation. In this case, oil and gas are in a critical equilibrium state and can move freely. When the hydraulic gradient is greater than 1, the total head decreases with depth more rapidly than the elevation head, leading to a progressive reduction in pressure head from top to bottom. Under such conditions, the resulting pressure difference produces a net downward force on oil and gas, which suppresses upward escape.

This analysis indicates that, in portions of the surrounding rock where the hydraulic gradient exceeds 1, the net pressure acting on gas bubbles is directed toward the cavern. As a result, bubbles neither escape along fractures nor remain trapped in the rock mass, but are instead driven into the cavern by groundwater flow during saturation.

The above discussion assumes vertical fractures as the potential escape paths for oil and gas. When the leakage path is an inclined fracture, the critical hydraulic gradient is modified by the inclination angle and is given by cos α, leading to a corresponding reduction in the threshold hydraulic gradient.

3.3. Testing of permeability coefficients and seepage analysis of reservoir rock masses

Obtaining the spatial distribution of rock permeability within the reservoir area is a prerequisite for three-dimensional seepage modelling. Physical indicators such as rock depth, core RQD and P-wave velocity are commonly used to establish empirical correlation equations for estimating permeability coefficients (Song et al., 2014). In addition, in situ hydraulic testing, fracture surveys and numerical seepage simulations of fracture networks can be employed to determine permeability more directly (Sun et al., 2006; Dai and Zhou, 2015). Kriging interpolation is

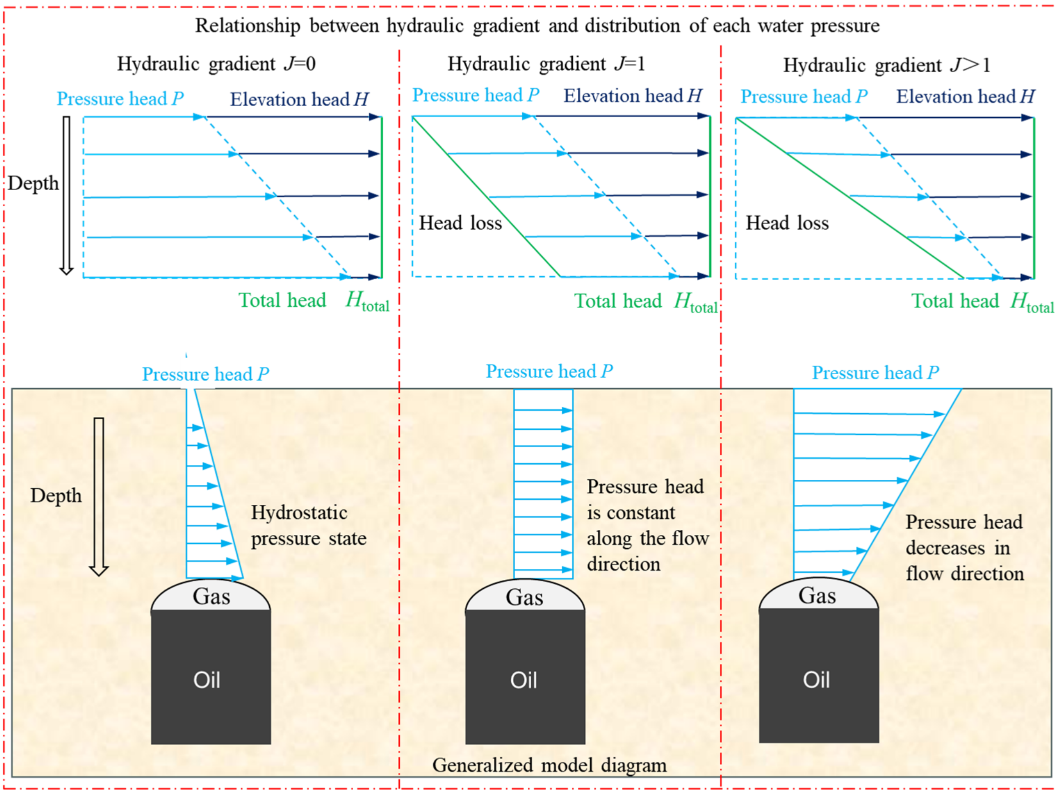

Fig. 5. Pore water pressure distribution under different hydraulic gradients.

then applied to generate a continuous spatial distribution of permeability coefficients over the entire reservoir area (Aoki, 2023).

During the construction stage, water levels in monitoring wells, recharge rates of water curtain boreholes and measured seepage inflows into the caverns are the main indicators used to characterise the spatial variability of rock permeability within the reservoir. Water-sealed underground oil storage caverns are typically equipped with dozens of groundwater monitoring wells, from which groundwater-level contour maps are constructed for the whole site (Wang et al., 2011). Zones exhibiting pronounced groundwater-level drawdown usually correspond to anomalous permeability regions, and time-series analysis of coupled datasets such as water curtain recharge, groundwater levels and seepage inflows has proven effective for evaluating water curtain performance and refining the inferred permeability field (Shi et al., 2018).

Given the comprehensive coverage of water curtain wells across the reservoir, an empirical relationship between water curtain recharge volume and the equivalent permeability coefficient of the surrounding rock can be established, allowing indirect determination of the spatial distribution of equivalent permeability (Zhang et al., 2015). In addition, the permeability coefficient for each well section can be estimated using a minimum-error procedure based on empirical seepage formulas, which refines the longitudinal zonation of hydraulic conductivity along individual boreholes (Xu et al., 2015; Jiang et al., 2022).

Analysis of seepage volume in underground oil storage caverns is a critical component of water sealing control, because it governs the design capacity of drainage pumps and the required storage volume of seepage ponds (Usmani et al., 2015). The main factors influencing seepage volume include the permeability of the surrounding rock, the hydraulic head difference and the effective seepage area (Shi et al., 2019). Methods for seepage evaluation include empirical formula approaches, numerical modelling and field testing (Wang et al., 2016). Empirical formulas are generally used to estimate seepage for individual wells and do not account for well-group interference (Zhang et al., 2017), whereas numerical analysis and field tests are more commonly adopted in engineering practice. Numerical methods place strict requirements on the hydrogeological model and the representation of the seepage structure: the model must capture the spatial variability of permeability and the complexity of drainage boundaries, while the seepage structure must reflect the permeability characteristics of major tectonic fractures (Sun and Zhao, 2010; Xu et al., 2021). Field testing methods include manual point-by-point measurements, statistics of drainage from cavern outlet pipes and statistics of artificially recharged water. Manual collection is labour-intensive and prone to missing critical seepage zones; drainage-pipe measurements are often affected by production water, and part of the artificially recharged water infiltrates the rock mass or is lost at drainage boundaries and geological discontinuities, complicating the back-analysis of seepage parameters.

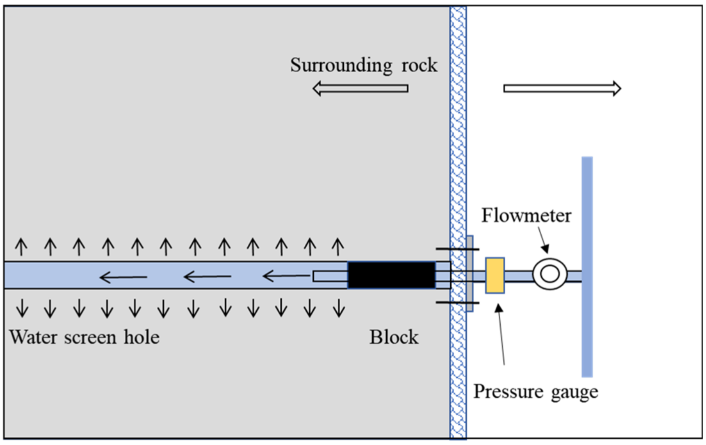

Fig. 6. Statistical method for water replenishment during construction period.

4. Water sealing control technology for underground oil storage caverns

The primary targets of water sealing control are concentrated seepage zones and water pressure failure zones. Concentrated seepage zones require "water plugging" measures to reduce seepage, whereas water pressure failure zones necessitate "water injection" to restore pore water pressure. The overall strategy for water sealing control is to optimise the technical parameters of water replenishment, seepage regulation, and seepage reduction (Xu et al., 2018). The objective is to minimise water seepage within the underground oil storage caverns while maintaining effective hydraulic sealing, thereby achieving the lowest possible life-cycle cost and the highest overall benefit for the cavern system.

4.1. Concentrated seepage zones

According to the relevant design code (China Sinopec., 2020), the allowable seepage volume is limited to 200 m^3/d per million cubic metres of reservoir capacity. On this basis, three-dimensional numerical modelling can be used to estimate an average permeability coefficient of about 1×10^{-8} m/s for the surrounding rock of a water-sealed cavern (Xue, 2010; Zhang, 2014). In practice, the reservoir is mainly enclosed by dense rock, with locally jointed zones. The permeability of dense rock generally ranges from approximately 1×10^{-11} to 1×10^{-9} m/s, whereas joint-intensive zones may reach 1×10^{-7} to 1×10^{-4} m/s (Usmani et al., 2015). Jointed regions with permeability coefficients significantly greater than 1×10^{-8} m/s are therefore identified as concentrated seepage zones. The most direct way to control seepage in such zones is to reduce their permeability to the design range.

For concentrated seepage zones, the water sealing control target is that the seepage volume should not exceed 200 m^3/d per million cubic metres of reservoir capacity. The main technical measures include: (i) optimisation of water curtain system parameters, (ii) grouting within the reservoir area to reduce seepage, and (iii) installation of anti-seepage support for the surrounding rock around the cavern. The seepage volume can be reduced by adjusting the spacing of recharge holes or lowering the recharge pressure. At the initial design stage, appropriately increasing the spacing of recharge holes within concentrated seepage zones helps to avoid a subsequent decline in the seepage-reduction efficiency of water curtain holes. When grouting is carried out from recharge boreholes, temporarily reducing the artificial water recharge pressure is an effective way to improve grout penetration; the recharge pressure should be restored to its normal value after the grout has fully set.

Seepage reduction in concentrated zones is achieved through a combination of borehole grouting, water curtain hole grouting, and curtain grouting. Grouting works are mainly focused on concentrated seepage zones and supplemented by post-grouting where necessary. The effective grouting thickness and the permeability coefficient of the treated rock mass are the principal indices used for grouting control. Engineering practice indicates that when the grouted thickness exceeds about 5 m, the equivalent permeability coefficient can be reduced economically to approximately 5×10^{-8} m/s, which meets the water sealing requirement. During grouting, slurry migrates towards the periphery of the borehole, and cement particles are deposited within water-conducting fractures at some distance from the hole, blocking the flow paths and lowering rock permeability (Cambefort, 1977; Houlsby, 1991). To overcome poor injectability associated with narrow fractures and clay-filled joints in the surrounding rock of water-sealed reservoirs (Yoshida et al., 2013; Okazaki et al., 2014a), finer cements or ultrafine cement materials can be adopted, and controlled suspension grouting (CSG) has been shown to provide improved seepage-reduction performance in gas storage projects.

Anti-seepage support of the surrounding rock further reduces seepage in concentrated zones. Rock bolts can restrict further opening and propagation of fractures, while sprayed impermeable fibre-reinforced concrete decreases the rate of elastic water release from the rock mass. In some gas storage caverns, pressurisation of the water curtain system has led to increased pore water pressure, larger surrounding rock displacements, and higher seepage volumes. After applying seepage-control reinforcements such as sprayed fibre-reinforced concrete, anchors, and post-grouting, both seepage and rock displacement were effectively controlled (Kurose et al., 2014b).

4.2. Hydraulic failure zones

Hydraulic failure zones are identified by jointly analysing the water curtain recharge volume and pore water pressure. During cavern excavation, fissure water loss along drainage boundaries and elastic release of the surrounding rock lead to rapid depletion of natural groundwater in the cavern area (Liu et al., 2009). If the recharge boreholes do not effectively intersect the fracture network inside the cavern, groundwater replenishment is delayed and pore water pressure may locally drop to approximately 0 MPa, which poses a significant risk of gas leakage. Zones where the recharge volume of water curtain boreholes remains essentially stable over a long period while pore water pressure continues to decline are therefore classified as hydraulic failure zones. The gas leakage incident that occurred at the Ravensworth gas reservoir in the United States in 1973 was attributed to insufficient local water recharge (Bérest, 1990). On this basis, Geostock engineers have emphasised that preventing the formation and extension of hydraulic failure zones is a primary concern in the design and operation of unlined rock caverns (Eric et al., 2005).

The objective of water sealing control in hydraulic failure zones is to restore and maintain pore water pressure above the storage pressure in the cavern. The main regulatory measures include optimisation of water curtain system parameters, seepage control and reduction within the underground oil storage caverns, and, when necessary, a reduction in cavern storage pressure. Pore water pressure can be restored by increasing the density of water curtain boreholes or by raising the artificial recharge pressure. Additional water curtain holes should intersect major joints at large angles to improve hydraulic connection and sealing efficiency. In the vicinity of faults, permeability on both sides is often very low; therefore, water curtain boreholes near a fault should be drilled through the fault plane to ensure connectivity and effective pressure transmission. Following excavation, elastic water release from the surrounding rock and outward expansion of the drainage boundary can promote the development of hydraulic failure zones (Okazaki et al., 2014b). Visible water leakage from the cavern should be grouted and sealed promptly to prevent further depletion of natural groundwater, and wet areas on the cavern wall should be sprayed with anti-seepage concrete in a timely manner to reduce the rate of elastic water release from the rock mass. In addition, reducing the cavern storage pressure to a level closer to the confining capacity of the overburden or the designed water sealing pressure can further mitigate the risk of gas leakage (Bérest, 1990).

4.3. Determination of technical parameters for water sealing regulation

The technical parameters of water sealing control are primarily determined by groundwater numerical simulation, physical model testing, and field testing. Numerical simulation and model testing allow rapid prediction of the pore water pressure distribution and seepage rates after implementation of a given water sealing control scheme, and can be carried out at relatively low technical cost (Li et al., 2009; Zhang et al., 2012; Li et al., 2016b; Li et al., 2017; Liu et al., 2021). For example, Qiao et al. (2024) numerically simulated groundwater flow in a coastal underground oil storage cavern to analyse the response of the seepage field under different water curtain layouts and operating conditions. Field tests should be carefully designed to control boundary conditions and operating parameters, and to record changes in water sealing performance in a systematic manner. In particular, monitoring data from concentrated seepage zones and hydraulic failure zones before and after parameter adjustment provides a direct basis for evaluating the effectiveness of the selected water sealing control scheme.

4.4. Evaluation of the effectiveness of water sealing regulation

4.4.1. Evaluation method of water sealing regulation effect

The effectiveness of water sealing control is evaluated using a combination of seepage measurements in the reservoir area, pore water pressure monitoring, water pressure testing, and airtightness testing. After the implementation of control measures in concentrated seepage zones, the seepage volume in the reservoir and the recharge rate of the water curtain system should both be reduced to, or below, the design values. Where seepage is difficult to quantify directly, the effectiveness of seepage reduction can be assessed indirectly through water pressure tests.

For hydraulic failure zones, the pore water pressure in the surrounding rock should exceed the storage pressure once water sealing control measures have been implemented. Airtightness testing of the oil storage cavern requires that the air pressure be maintained for a specified period; if the pressure drop remains within the allowable range during this period, the cavern is considered to satisfy the airtightness requirements (Okazaki et al., 2014c).

4.4.2. Comprehensive quantitative indicators of water sealing efficiency

Fig. 6 presents the conceptual diagram of the integrated quantitative index of water sealing efficiency proposed by Liu et al. (2021). As illustrated in Fig. 7, the defined area A represents the water sealing safety margin, and the total head H decreases gradually from the top to the bottom until it reaches the storage pressure P. When the water sealing safety margin A increases, the seepage volume also increases. Liu et al. (2021) therefore established a comprehensive quantitative index of water sealing efficiency, I_e, defined as the ratio of the 'water sealing safety margin' to 'seepage volume':

$$I_e = \frac{Al}{vt} \tag{9}$$

where l is the length of the cave chamber, v is the seepage rate of the cave reservoir, and t is the characteristic time. The larger the value of I_e, the higher the degree of water seal security provided by the unit of seepage.

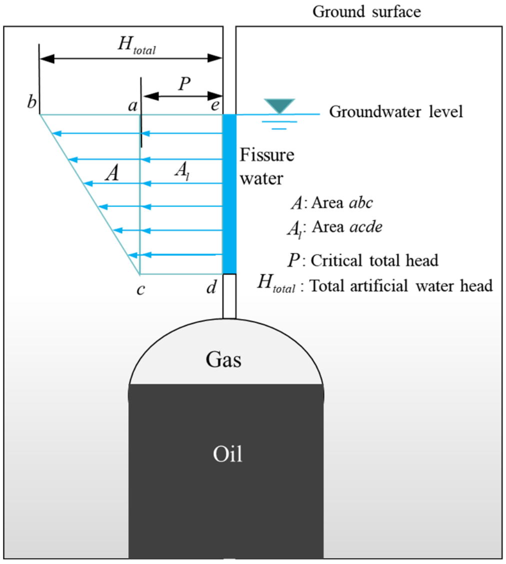

Fig. 7 Conceptual diagram of a comprehensive quantitative indicator of water sealing efficiency.

5. Theoretical innovation and equipment development

(1) Law of bubble motion in pressurised fissure flow

The motion of gas bubbles in pressurised fractures provides a fundamental basis for understanding hydraulic sealing mechanisms and for evaluating the effectiveness of water sealing control. Future work should couple realistic fracture geometries with two-phase flow simulations and laboratory experiments. Transparent or acrylic fracture models, combined with high-speed imaging, can be used to observe bubble migration, trapping, and collapse under controlled hydraulic gradients, and to calibrate numerical two-phase seepage models that have been applied in underground gas storage engineering (Jiao et al., 2023). These studies will refine quantitative effectiveness criteria for water sealing, such as critical hydraulic gradients and safety margins, beyond the classical formulations proposed by Gao and Gu (1997).

(2) Establishment of recharge grading standards for water curtain holes

Recharge grading standards for water curtain holes are important for the rapid identification of concentrated seepage zones and hydraulic failure regions in underground oil storage caverns. Under fixed design parameters such as hole length, recharge pressure, and spacing, recharge capacity is mainly controlled by the permeability of the surrounding rock mass. Time series analyses that combine water curtain recharge, groundwater level response and numerical modelling already provide a basis for probabilistic evaluation of water curtain performance in operating reservoirs (Zhang et al., 2022). On this basis, a unified grading system for recharge behaviour can be formulated and linked directly to permeability classes of the surrounding rock, which in turn supports targeted adjustment of recharge pressure, hole spacing, and layout.

(3) Improvement of grouting materials for concentrated seepage zones

In concentrated seepage zones, grouting materials must combine low permeability with long term durability under repeated hydraulic loading. Conventional Portland cement slurry often shows limited penetration in fine fractures, which can lead to secondary water inflow as the hydraulic head increases. Laboratory studies on micro fracture grouting have shown that ultrafine cements and optimised grouting pressure significantly improve injectability and reduce fracture permeability in millimetre-scale and sub-millimetre-scale fractures (Wang et al., 2020). Building on such results and on the observations of Toyoda et al. (2018), future research should focus on composite ultrafine grouts designed for fissures with apertures of 10 to 30 micrometres, and should include long-term performance tests under coupled hydro mechanical and chemical conditions.

(4) Development of large-section, high sidewall grouting equipment

The sidewalls of underground oil storage caverns can reach heights greater than 30 m, and existing grouting rigs and lifting platforms are often insufficient for systematic and safe post excavation grouting, especially in the middle and lower parts of large chambers. Specialised equipment is needed that integrates precise positioning, adjustable injection ports, and safe operation on high sidewalls. Such equipment would allow planned grouting thickness and coverage to be achieved more reliably and would support staged grouting campaigns that follow the evolution of the seepage field during construction and early operation.

(5) Development of precision equipment for seepage control and clearing of water curtain holes

Water curtain holes that intersect concentrated seepage zones frequently show very high recharge volumes and are key targets for seepage reduction. In these locations, partial sealing of specific intervals, followed by restoration of normal recharge service, requires accurate positioning, selective grouting, and reliable post-grouting cleaning. Dedicated precision tools for grouting and dredging in long and inclined boreholes are therefore needed, so that targeted “plug and restore” strategies can be implemented without compromising the overall effectiveness of the water curtain system.

(6) Optimisation of water curtain hole configuration

The configuration of the water curtain system has a direct influence on hydraulic sealing performance and long-term maintainability. Dual loop circulating water systems can reduce clogging of fractures by suspended particles and microbial products in the recharge water. At the same time, careful control of hole length can avoid unwanted hydraulic connections between high-permeability seepage channels and the cavern. Recent developments in experimental systems for grouting in rough fractured rock masses provide useful analogues for understanding how flow concentrates along preferential pathways (Li et al., 2024). Water curtain design should therefore consider fracture orientation and anisotropy, and optimise hole spacing, length and orientation with respect to the dominant fracture sets, in order to improve sealing reliability and to facilitate local seepage control.

6. Conclusions

(1) This study clarifies the core theory of water sealing control in underground oil storage caverns. Two aspects are emphasised: sealing effectiveness criteria and seepage analysis. The effectiveness criteria are defined by

a critical groundwater level and a critical hydraulic gradient. A water curtain system installed above the caverns is essential to maintain effective water sealing, as it stabilises groundwater levels and sustains a positive hydraulic gradient between the water curtain and the cavern vault. Seepage analysis relies on field monitoring and numerical simulation, which must reflect the spatial heterogeneity of hydrogeological parameters and fracture flow.

(2) On this theoretical basis, the role of hydraulic gradient in sealing effectiveness is clarified. When the hydraulic gradient in the surrounding rock exceeds unity, gas bubbles experience a pressure difference directed toward the cavern, which suppresses upward migration. Under saturated conditions, this gradient compresses gas in fractures and drives it into the cavern, achieving hydraulic containment. A systematic framework for water sealing control technologies is then established, in which concentrated seepage zones and hydraulic failure regions are the main control targets. Plugging measures are used to reduce inflow in seepage zones, while artificial recharge restores pore water pressure in failure regions. Key measures include optimisation of artificial water replenishment, grouting in the reservoir area, seepage reduction, and reinforcement of the surrounding rock to prevent leakage.

(3) The work further outlines key directions for strengthening water sealing control. These include improving understanding of bubble migration in pressurised fractures, developing recharge grading standards for water curtain holes, enhancing the performance of grouting materials in concentrated seepage zones, designing specialised grouting equipment for large-section and high-sidewall conditions, developing precision tools for seepage reduction and hole clearing, and optimising water curtain system configuration to limit clogging and improve long-term sealing reliability.

Author Contributions

X.S.: writing—original draft preparation, writing—reviewing and editing, data curation, conceptualization, software, methodology, software; J.Z.: data curation, writing—reviewing and editing, visualization, investigation, supervision; J.C.: writing—reviewing and editing, visualization, investigation, software, validation. All authors have read and agreed to the published version of the manuscript.

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Conflict of interest

The authors declare no conflict of interest.

Use of AI and AI-assisted Technologies

No AI tools were utilized for this paper.

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