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A groundwater seal evaluation method based on water inflow for underground oil storage caverns

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ABSTRACT

A novel groundwater seal evaluation method based on water inflow for is proposed. The groundwater seepage field and the water inflow of an oil storage cavern obtained with different water curtain parameters are studied via numerical simulations. The sensitivity of water inflow to various water curtain hole parameters is studied based on regression analysis. A novel concept of minimum water inflow is proposed, and the weak area of the groundwater seal is revealed. The results indicate that the water curtain pressure (*p*), the length of the water curtain hole (*l*), and the inclination angle (*a*) are positively correlated with water inflow, while the water curtain hole spacing (*s*) is negatively correlated with water inflow. The relative influences of water curtain system parameters on the groundwater seal of the oil storage cavern are ranked as follows: $p > l > s > a$.

1. Introduction

Oil is the economic lifeline of any country. Maintaining a safe and stable oil supply in the form of adequate reserves is an essential condition for ensuring social stability and economic development (Pan, 2004; Naithani, 2012). The construction of groundwater-sealed oil storage caverns has gradually become the preferred choice for maintaining strategic petroleum reserves worldwide owing to the geographical adaptability, high degree of safety, and economical land use associated with this approach (Lu, 1998; Mawire, 2013). Oil storage caverns are constructed by excavation conducted in rock masses lying below the water table (Lin et al., 2015). Groundwater sealing is realized through the seepage of ground water through the rock mass (Chen et al., 2010). Underground oil storage caverns (UOSC) must meet the following three conditions: (1) the proportion of oil and gas is less than the proportion of water; (2) oil, gas, and water does not decompose or dissolve under normal conditions; (3) the water pressure around the cavern is greater than the storage pressure throughout the term of service. Obviously, the first two conditions are met naturally because of the physical and chemical properties of oil and gas. However, the third condition depends on engineering geology, hydrogeological conditions, and the implementation of artificial control measures.

With respect to the third condition, Aberg (1977) studied the relationship between water injection pressure and the storage pressure of cavern reservoirs without considering the influence of gravity, friction, and capillarity. The results of the study demonstrated that the groundwater seal of a reservoir can be guaranteed when the vertical hydraulic gradient is greater than 1. Later, Goodall et al. (1988) extended this criterion on the basis of the past work of Aberg. In actual design, the criterion for guaranteeing the groundwater seal of a reservoir can be based on a simpler principle: the water pressure increases continuously from all possible leakage paths. However, sealing against gas leakage will not be guaranteed (Benardos and Kaliampakos, 2005; Cha et al., 2006). This fundamental research verified that groundwater-sealed caverns are theoretically feasible.

Ensuring a stable groundwater seal mainly depends on manual control measures because the condition of the surrounding rock is difficult to change (Goel et al., 2012; He, 2011; Shi and Liu, 2010). Here, the rational allocation of a water curtain system (WCS) plays a key role (Li et al., 2005). The sealing of a cavern reservoir is guaranteed by a reasonable hydraulic gradient and optimized design based on the hydrogeological characteristics of the storage area obtained by hydrological observation, monitoring, testing, and numerical simulation. A WCS consists of water curtain tunnels and a series of water curtain drilling holes. The water curtain drilling holes connect with the water curtain tunnel (Tan et al., 2006; Wang et al., 2015b). The hydraulic pressure is maintained by injecting an appropriate amount of water. The injected water can increase the pore water pressure around the oil

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storage cavern while maintaining a stable groundwater table to prevent oil spills (Li et al., 2009b). WCS has been extensively studied. They conducted specific physical model tests. The tests indicated that the water curtain hole spacing, the critical gas pressure, and the number and spacing of oil storage caverns have a significant influence on the cavern seal. Tan et al. (2006) employed numerical simulation in a seepage field analysis of Guangdong Shantou liquid propane gas (LPG) storage to demonstrate that a WCS is an effective method of preventing gas leakage. The study of the Pyongtaek LPG reservoir in South Korea also demonstrated that a vertical water curtain and a horizontal water curtain can guarantee the groundwater seal of oil storage caverns (Park et al., 2005). Zhang et al. (2013) studied the artificial water curtain seepage field of UOSC. In addition, WCS plays an important role in the safe storage and protection of groundwater resources (Liu, 2009). Gao and Gu (1997) proposed various principles of water curtain design based on an analysis of the factors influencing water curtain performance. Lindblom (1989) investigated the water curtain performance of gas storage caverns in Sweden. Zimmels et al. (2006) and Da Costa et al. (2014) have extended the principles of water curtain design, and offered beneficial suggestions for practical installations. Li et al. (2012) studied the seepage characteristics of fractured rock masses and the temporal and spatial evolution of the groundwater seepage field using an equivalent continuum approach. Wang et al. (2015a); (Wang et al., 2015b) studied the design and testing of WCS for underground oil storage facilities in China, and provided a useful reference for the design of WCS.

While these past research efforts related to the optimization of WCS for UOSC and groundwater seal evaluation have considerable theoretical value and engineering significance, most of these studies have evaluated the groundwater seal and performance of oil storage caverns as a whole. However, little research related to groundwater seal optimization has been conducted from the perspective of water curtain hole design. In a past study, the influence of the geometric parameters of water curtain holes on WCS performance was investigated by water curtain drilling experiments. The results showed that the leakage of oil is affected by the water curtain spacing, the storage pressure, and the layout of the oil storage cavern. However, this study did not consider the influence of the WCS on the groundwater seal, and provided minimal guidance for the selection of WCS parameters. Some affecting parameters such as borehole elevation above cavern crown, gas pressure, operation time, hydraulic conductivity and porosity are considered and detailed studies is given by Ravandi et al. (2016, 2017a). Presently, no definite conclusions are uniformly agreed upon regarding the most significant water curtain parameters affecting the groundwater seal of caverns. To guide the process of WCS parameter optimization, we first conduct a sensitivity analysis of the groundwater seal of caverns relative to WCS parameters. Therefore, the present study applies a combination of numerical computations and multivariate regression analysis to this problem. A new groundwater seal evaluation method based on water inflow for UOSC is proposed. Some suggestions regarding the optimization and selection of water curtain hole parameters are proposed. In addition, a regression forecasting model is established to forecast the water inflow of caverns.

2. Water inflow based groundwater seal evaluation method for underground oil storage

A numerical model of UOSC and WCS is established according to practical engineering principles. Then, the seepage field is simulated and the water inflow is calculated by this model. The simulated seepage field reveals the weak point of the groundwater seal. Then, the water inflow is employed to evaluate the influence of water curtain hole parameters on the groundwater seal of UOSC. Multi-factor regression analysis is employed to evaluate the relative sensitivity of the groundwater seal to the various water curtain parameters. The established regression model can then be applied for predicting water inflow according to the water curtain parameters, and also evaluate the rationality of the selected water curtain parameters based on the calculated water inflow.

2.1. Governing equation

The governing equations of the seepage field are developed from Darcy's law, and are given with initial conditions and boundary conditions as

$$\rho S\frac{\partial p}{\partial t} + \nabla\cdot\rho\left[-\frac{\kappa}{\mu}(\nabla p + \rho g\nabla D)\right] = Q_{\mathrm{m}} \tag{1}$$

where S is the coefficient of water storage (1/Pa), p is the pore water pressure (Pa), t is time (s), ρ is the density of water (kg/m^3), κ is the permeability (m^2), μ is water dynamic viscosity (Pa·s), g is gravitational acceleration (m/s^2), D is the pressure head (m), and Q_{m} is the water flow (m^3/s). For an incompressible fluid, the velocity of seepage υ (m/s) is obtained by (1) without considering initial conditions and boundary conditions:

$$\upsilon = -\frac{\kappa}{\mu}\nabla p \tag{2}$$

2.2. Water inflow equation

The influence of permeability, water pressure, and chamber shape indicate that the water inflow may be different in different areas. The water inflow Q (m^3/s) is therefore calculated as

$$Q = \iint_{\Sigma} \upsilon\cdot ds \tag{3}$$

where $\sum$ is the area of integration and ds is an infinitesimal area unit of integration.

2.3. Initial and boundary conditions

Under conditions of a symmetrical boundary or a no-flow boundary in the seepage boundary region, (3) is fixed as

$$-\mathbf{n}\cdot\rho\upsilon = 0 \tag{4}$$

where $\mathbf{n}$ is a vector of the boundary normal, and

$$p = p_w \tag{5}$$

$$p_0 = \rho_0 g h_0 \tag{6}$$

wherep_w is the water curtain pressure (Pa), p_0 is the oil pressure (Pa), ρ_0 is density of oil (i.e., 850 kg/m^3), andh_0 is the height of the oil surface relative to the bottom of the storage cavern.

2.4. Evaluation of groundwater seal parameters

From the underground cavern storage mechanism, we note that it is necessary to maintain an appropriate groundwater seepage pressure during cavern construction and operation. However, limiting the inflow of water during construction and maintaining proper water inflow during operation are the key factors. In a homogeneous medium, a positive correlation exists between the groundwater seal of an oil storage cavern and inflow of the cavern. Therefore, the water inflow from the cavern is selected as the index for evaluating the groundwater seal of the cavern. When the values of p at specific locations around the oil storage cavern are equal to the values of p_0 at these locations, the oil storage cavern is in a critical groundwater seal state. The water inflow in this critical state is denoted as Q_0. The numerical simulation is carried out in the design stage, which is used to evaluate the design parameters. In numerical simulation, studies are carried out based on the geology and hydrology of the reservoir area. Relevant standards are