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Design and test aspects of a water curtain system for underground oil storage caverns in China

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ABSTRACT

A water curtain system consists of many boreholes arranged in a systematic manner. To maintain tight seals when storing substances (e.g., crude oil), water curtain systems are usually employed for underground storage in hard rock. With the aid of these systems, stable seepage fields develop around storage caverns, and hydrodynamic containment is achieved in the storage caverns. In this paper, several issues regarding the design and testing of a water curtain system in underground oil storage caverns in China were investigated. Regarding the design of these systems, natural and artificial containments were compared, and the role of hydrogeology in the selection of containment was explored. A literature review on the geometrical parameters of these systems used in storage caverns was performed and provided reference for the design of the proposed water curtain system. The influence of rock joint orientations on the arrangement of boreholes in the curtain system was addressed; it was concluded that the boreholes should be arranged perpendicularly to the dominant joints to obtain a system with good performance. Regarding the testing of these systems, a procedure used to evaluate the performance of the proposed water curtain system was developed. A method used to determine the interconnectivity of the system was also developed, and an improved test procedure was proposed based on the test results. A curtain system injection test was performed, and the groundwater flow rates into both the water curtain system and the storage caverns were measured. It was shown that the groundwater flow rates were dominated by the groundwater flow in the rock joints and the areas where high groundwater flow rates around the cavern surfaces coincided with those where high groundwater flow rates appeared at water curtain boreholes.

1. Introduction

China's demand for oil is increasing due to its rapid economic development in recent years. In 2012, China consumed a total of 0.47 billion tons of oil, among which 58% (i.e., 0.29 billion tons) was imported from other countries (Tian, 2013). A safe and stable oil supply is critical to China's sustainable economic and social development. One method of oil storage is in hard rock, and underground oil storage with a water curtain system is superior to other methods because it has a good safety performance, is low cost and is environmental friendly. As a result, this method has become an important method for national strategic oil storage in China.

The basic principle of underground storage with a water curtain system ensures that the groundwater pressure surrounding the storage caverns is higher than the pressure in the stored oil and/or oil gas; this prevents oil leakage via seepage into the surrounding rock mass. Aberg (1977) postulated that if the vertical hydraulic gradient around the storage caverns is greater than unity, then the stored petroleum gas will not leak through the surrounding host rock mass. Goodall et al. (1988) proposed a generalized criterion that no leakage will occur as long as the water pressure gradients along all possible escape paths are positive. Lindblom (1989) presented the performance test and long-term operational monitoring results of a water curtain system for a real gas storage site in Sweden. The influence of the curtain and storage pressures on the groundwater inflow rates into the curtain system and caverns were measured. Liang and Lindblom (1994) studied the influence of different factors on gas storage capacity and concluded that the critical gas pressure is considerably less than the natural hydrostatic pressure around the caverns and is also less than the water curtain pressure.

Underground storage of oil and gas in hard rock with a water curtain system is now an accepted technique worldwide.

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Kiyoyama (1990) described current modern technologies used in Japanese underground oil storage. Hoshino (1993) presented a geological stability study for oil storage in orogenic areas. Lee et al. (1996) discussed the design and construction aspects of unlined oil storage caverns in Korea. Benardos and Kaliampakos (2005) presented the details of the construction of unlined oil storage caverns in limestone formations in Greece. Park et al. (2005) highlighted geo-engineering problems and solutions regarding the design an LPG storage terminal beneath a lake. The above studies provide valuable engineering experiences for the design and construction of an underground storage facility.

Most previous studies have focused on the overall performance of the storage facility; there are few studies that have investigated the design and testing of water curtain systems. Rehbinder et al. (1988) developed an experimental setup to investigate the no-outflow criterion from a cavity using water curtain boreholes around the cavity. In their study, the relationships between the number of water curtain boreholes and the pressures in the cavity and in the water curtain were obtained for the no-outflow criterion of the cavity using water curtain boreholes. Li et al. (2009) then developed an experimental physical modeling system to evaluate the performance of water curtain systems with different geometrical parameters. Their experimental results show that leakage is strongly influenced by the spacing of the water curtain boreholes, the stored pressure and the layout of the storage caverns. Most previous studies on the performance of a water curtain system were performed in laboratories under simple conditions. However, due to the complexities of rock mass and hydrogeological conditions in the storage caverns, a practical study of the design and testing of a water curtain system would be valuable. In this study, several design and testing issues regarding water curtain systems are presented using a pilot underground oil storage facility in China as an example.

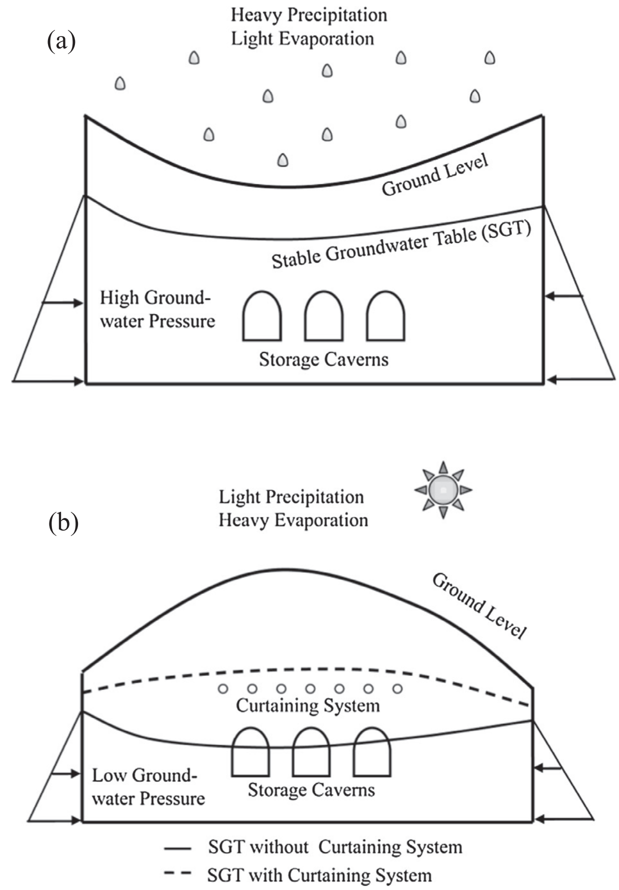

Fig. 1. Containment methods for underground storage caverns: (a) natural containment and (b) artificial containment.

2. Design of a water curtain system

2.1. Natural and artificial hydrodynamic containments

The proper function of oil storage in underground caverns relies on the following three conditions:

(1) The specific gravity of the oil must be less than that of water.
(2) The oil is anti-decomposition and insoluble in water.
(3) The groundwater pressure around the caverns must be higher than the stored oil pressure.

The first two conditions are satisfied due to the natural physico-chemical properties of oil, while the third condition (i.e., hydrodynamic containment) depends on the hydrogeological conditions of the project site. The basic principle of efficient underground storage relies on the groundwater pressure around the storage caverns being higher than the pressure of the stored oil; this prevents oil leakage into the rock mass. To satisfy the third condition, underground storage caverns should be operated with a proper relationship between the storage oil pressure and groundwater pressure around the caverns. This relationship could be maintained naturally (i.e., using the natural groundwater table) or artificially (i.e., using a water curtain system).

Natural maintenance of this relationship implies that the hydrodynamic containment of the storage caverns would be maintained by the supply of natural groundwater buried in formations and natural precipitation. As shown in Fig. 1a, this method is applicable for underground oil storage facilities in regions where the stable groundwater table is high compared to the elevation of the storage caverns and the groundwater supply is sufficient (Lindblom, 1989). Artificial maintenance is needed when the hydrodynamic containment of storage caverns would not be maintained by natural groundwater and precipitation, and therefore, a water curtain system would be required. This artificial method is applicable in facilities in regions where the groundwater table is low compared to the elevation of the storage caverns or if the groundwater supply is insufficient, as shown in Fig. 1b. In practice, whether a water curtain system is used depends on the hydrogeological conditions of the facility.

2.2. Literature review of the design of a water curtain system

The geometrical parameters of water curtain systems include the length and spacing of their boreholes as well as the elevation difference between the boreholes and the cavern crown. Table 1 lists the details of water curtain systems for underground storage caverns in Greece, Norway, Korea and China. The storage substances are primarily compressed air, liquefied petroleum gas and crude oil; the rock types are primarily granite, tuff, diorite and andesite. Three arrangements of boreholes in the water curtain systems were employed in the caverns: tilting, horizontal and horizontal–vertical combination. Due to different hydrogeological conditions in different storage caverns, borehole spacing typically ranges from 7 to 20 m, while the elevation difference ranges from 12 to 31.2 m.

In general, storage caverns are characterized by

(1) A strong and stable rock mass.
(2) A location near the sea.