Tunnelling and Underground Space Technology 71 (2018) 466–477

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

journal homepage: www.elsevier.com/locate/tust

Hydro-geochemical analysis of the interplay between the groundwater, host rock and water curtain system for an underground oil storage facility

Zhechao Wang[a,b,*], Yoann Glais[c], Liping Qiao[a], Anda Huang[b], Jie Liu[b]

[a] Key Laboratory of Ministry of Education on Safe Mining of Deep Metal Mines, Northeastern University, Shenyang, Liaoning 110004, China
[b] School of Civil Engineering, Shandong University, Jinan, Shandong 250061, China
[c] Civil and Mechanical Engineering Laboratory, INSA Rennes, Rennes, Ille-et-Vilaine, 35708, France

ARTICLE INFO

Keywords:
Underground storage caverns
Containment property
Water curtain system
Ion concentration
Statistical analysis

ABSTRACT

Hydro-geochemical analysis was performed to investigate the interplay between the groundwater, host rock and water curtain system for the start-up of a pilot underground oil storage facility in China. 54 groundwater samples were collected and analyzed to obtain the characteristics of the hydro-geochemical environment evolution for the start-up period. The groundwater-rock mass interaction was studied with comparing the changes in the ion concentrations, pH values and total dissolved solid concentrations in the groundwater and a mineralogical analysis of the host rock. The groundwater-water curtain system interaction was identified using statistical analysis of the similarity in chemical contents in the groundwater samples. A mixing calculation was performed to evaluate the mixing ratios of the water curtain system, background water and oil/vapor in the seepage water into the storage caverns. It was concluded that calcium carbonate equilibrium is the predominant chemical reaction. The 54 groundwater samples could be classified into 5 clusters. Among the 5 clusters, there is one cluster showing that the tap water injected to the water curtain system is similar in chemical contents to those in the monitoring boreholes around the facility, which confirms the efficiency of the water curtain system for the start-up of the facility. It was found that the two dominant factors influencing the evolution of groundwater chemical content were host rock dissolution and groundwater seepage. Most of seepage water was originated from oil/vapor and water curtain system while the percentage from the background water was almost zero in the start-up period of the facility.

1. Introduction

Chinese economic growth is synonymous with an increasing demand on natural resources. China started national storage strategy in 1990s, in which a total of 80 million tons of oil was planned to be stored to ensure the supply of oil for the country. However, the consumption of oil has increased dramatically since 2000s. In 2016, a total of 562.0 million tons of oil was consumed in China, with 378.3 million tons being imported from foreign countries (Tian, 2017). It can be expected that more national oil storage facilities will be constructed in China in the following years. Hydrocarbons energy storage, then, appears to be a good and economic solution to respond to the sudden demands on supply because it is able to reduce expenditure costs during the winter periods or at times of high demand when natural resources become more expensive. When compared to above ground storage tank facilities, underground storage provides significantly greater and cheaper storage volumes and when carefully constructed and monitored, added levels of safety. Hydrocarbon resources can be stored in a state of liquefied petroleum gas (Goodall et al., 1998), gas (Liang and Lindblom, 1994; Lu, 1998; Yang and Guan, 2010; Kim et al., 2007), or crude oil (Shi and Liu, 2010).

As a type of underground cavern groups, the storage facilities are usually constructed in rock mass of good quality. There is no much concern on the stability issues of the caverns as what has been observed in caverns in hydro-electrical industry (Duan et al., 2017; Feng et al., 2017); the core issue is assessing containment properties of the facility (Qiao et al., 2017a, 2017b; Wang et al., 2017). The basic principle storing LPG or crude oil in unlined rock caverns is that the groundwater pressure around the caverns should be higher than the pressure of the stored product to prevent leakage toward the surrounding rock mass. This pressure difference is ensured by a water-sealing system. Goodall et al. (1998) highlighted that leakage does not occur if the water pressure increases along all possible escape paths. Many studies on the technique of underground storage with a water curtain system have been performed worldwide. Kiyoyama (1990) was the first to introduce the concept and the basic considerations for underground crude oil

---

[*] Corresponding author at: Key Laboratory of Ministry of Education on Safe Mining of Deep Metal Mines, Northeastern University, Shenyang, Liaoning 110004, China.
E-mail addresses: wang_zhechao@hotmail.com, wangzhechao@mail.neu.edu.cn (Z. Wang).

http://dx.doi.org/10.1016/j.tust.2017.10.001
Received 26 April 2017; Received in revised form 10 September 2017; Accepted 10 October 2017

storage technology in Japan. Hoshino (1993) then presented a study on the geological stability in orogenic areas for underground facilities. Later, Lee et al. (1996) introduced the design and construction aspects of unlined oil storage caverns in rock. Lee and Song (2003) investigated mechanical and hydrological stability analyses of the storage caverns. Benardos and Kaliampakos (2005) discussed their experience in Greece during the construction of unlined oil storage caverns in limestone formations. Park et al. (2005) presented the problems they encountered in their geo-engineering approaches of a Liquefied Petroleum Gas (LPG) storage terminal underneath a lake. Li et al. (2014) used the discrete element method to investigate the role of joints in hydro-mechanical behavior. Wang et al. (2015a) investigated the effects of the construction sequence and drainage conditions on the hydro-mechanical behavior of a pilot underground storage facility in China. Several aspects of designing and hydraulically testing water curtain systems were also studied based on the practice of the pilot facility (Li et al., 2014; Wang et al., 2015b, 2015c, 2017; Qiao et al., 2017).

In the community of engineering geology and geotechnical engineering, hydro-geochemical analysis have been used to evaluate the impacts of nuclear waste disposal (Herman, 1989; Wood, 1993; Chen et al., 2015), general hazardous waste (Langer, 1993), tunnel construction (Raposo et al., 2010; Qiao et al., 2017a,b), landslide (Chigira et al., 2006) and foundation consolidation and settlement (Wang et al., 2012; Wang and Wong, 2016, 2017) on the geological environment. In particular, hydro-geochemical analysis has been used to characterize the groundwater systems around underground storage facilities for the operation of facilities. Jezerský (2007) conducted a study on the hydrochemistry of a deep gas storage cavern in the Czech Republic. The results of the water-quality monitoring of the deep groundwater seeps have been used in estimating the containment properties of the rock mass near the storage caverns. While in Korea, Lee et al. (2007) used a statistical approach to analyze the hydro-geochemical features of the groundwater in a LGP cavern. Moyce et al. (2014) investigated the geochemical evolution of the groundwater in the disposal of nuclear waste over a 15-year period. Gimeno et al. (2014) hydro-geochemically characterized and modeled the groundwater in a potential geological repository for spent nuclear fuel in crystalline rocks at Laxemar, Sweden. Finally, multivariate statistical analysis of groundwater is an approach that has been developed in many publications, especially by Lee et al. (2008, 2010) who analyzed the hydro-geochemistry of groundwater for an underground LGP facility in Korea.

All the above studies are being considered as valuable experiences in the construction and operation of underground storage facilities. However, the investigations on the start-up performance of the facilities are limited. The star-up period denotes from the start of use of the facility to the time when the system consisting of rock mass, groundwater, and water curtain system stabilizes with the facility being fully loaded. In the start-up period, the containment property of the facility is subject to mutual effects of the storage of oil in caverns and the injection of water in water curtain system. In the same time, the background groundwater is mixed with the injected water and the oil/vapors. The hydro-geochemical analysis will provide an insight to the start-up performance of the facilities through the exploration of between the groundwater, host rock and water curtain system, such as the impact of oil storage on hydro-geochemical environment, the activity of groundwater-rock mass chemical reaction and the efficiency of water curtain system. In this study, a total of 54 groundwater samples were collected from different locations in 5 collection sessions around a pilot underground oil storage facility in China. The first two sessions were performed before the operation of the facility and the other three sessions were within the first year from the start-up of the facility. The groundwater-rock mass interaction was investigated using the evolution of groundwater chemical contents and a mineralogical analysis of the rock mass. The groundwater-water curtain system interaction was analyzed using statistical analysis of the groundwater chemical contents. The two dominant factors influencing the evolution of groundwater chemical contents were identified as host rock dissolution and groundwater seepage (Lee et al., 2007). The efficiency of the water curtain system was evaluated using the analysis results. A mixing calculation was performed to evaluate the mixing ratios of the water curtain system, background water and oil/vapor in the seepage water into the storage caverns.

2. Site description

2.1. Geology and hydrogeology

The oil-storage facility is located in a granitic matrix from the Cretaceous and the Proterozoicus ages. The two dominating rock types are a reddish-grey granite, medium-to coarse-grained rock with a pronounced gneissic foliation and fine-grained aplite. However, some other minor rock types can be found such as diorite and amphibolite but representing less than 10% of the rock mass. In order to characterize the rock mass, a rock classification have been performed, according to Q-system, which have revealed that over 80% of the Q-values belong to fair or very good rock mass type (Wang et al., 2015a). This result assures the excellent rock conditions for the oil storage facility's construction safety as the rock material is described as generally competent and unweathered.

The average annual precipitation in 20 years have been calculated as 736.2 mm which mainly (70%) comes from the heavy rains occurring between June and September. Regarding the steep slope of ground surface the supply from atmospheric precipitation into the rock mass is negligible, which is confirmed by the infiltration coefficient of 0.073. A long-term groundwater level observations, hydro-geochemical and permeability tests analysis have been conducted in 15 vertical boreholes with a diameter of 75 mm and depths from 163 to 415 m around the facility in the pre-construction period. From those studies, it was found that the groundwater level varies with the topography and the permeability of the rock mass varies from 1×10^{-5} to 1×10^{-3} m/d, with a majority of 1×10^{-4} m/d.

2.2. Design and construction

This facility is composed of nine storage caverns, access tunnels and water curtain tunnels. Fig. 1 shows the layout of underground structures. The caverns are supposed to be left unlined, parallel to one another in the direction of N50°W. Each of them is 20 m wide, 30 m high and 500–700 m long. The access tunnels, horseshoe-shaped such as the caverns, are 7.5 m wide and 8.5 m high. Their elevation fluctuates from El. (+) 70 m at the entry level to El. (−) 50 m at the floor level of storage caverns, with a slope of about 8% between these two levels. The water curtain tunnels are also horseshoe-shaped and measure 4.5 m wide for 5.5 m high. The elevation of the water curtain tunnels is El. (+) 5 m, which is 25 m above the storage caverns. On the side walls of the tunnels, water curtain boreholes with a dimeter of 180 mm were

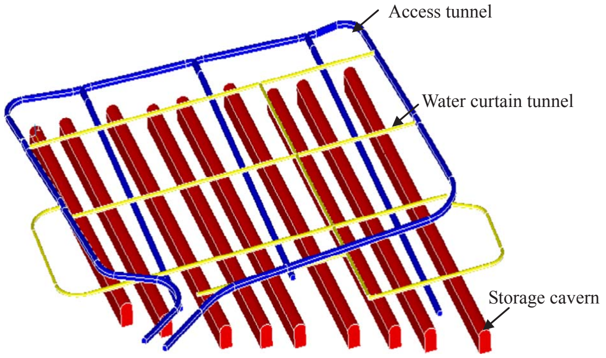

Fig. 1. Layout of underground structures of the pilot underground oil storage facility.