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Analysis of support requirements for underground water-sealed oil storage cavern in China

Jie Liu[a], Xing-Dong Zhao[a,*], Shu-Jing Zhang[a], Lian-Ku Xie[a,b]

[a] School of Resources & Civil Engineering, Northeastern University, Shenyang, Liaoning 110819, China
[b] Beijing General Research Institute of Mining & Metallurgy, Beijing 100160, China

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ABSTRACT

The aim of this study is to provide a sound support design for a large-scale underground water-sealed oil storage facility in China. The lithology of this study area consists of reddish-gray, medium-coarse grained granites interpenetrated by diabase, amphibole dioritic porphyrite and aplite. In order to obtain the geotechnical properties of intact rocks and rock masses, detailed field and laboratory studies were carried out. Rock masses at three sites were characterized in terms of Rock Mass Rating (RMR), Rock Mass Quality (*Q*-system) and Geological Strength Index (GSI), and then rock mass properties of underground caverns were estimated, accordingly. The support systems obtained from empirical methods were analyzed using FLAC3D commercial software considering the effect of the water curtain system. The maximum thickness of plastic zones and the maximum total displacement occurred around underground caverns after installing the support systems suggested by the empirical methods were compared to the unsupported case. The results show that more reliable support design could be obtained by using both empirical rock mass classifications and numerical analysis method.

1. Introduction

China is short of oil resources and the contradiction between supply and demand has been increasingly prominent in recent years. In 2016, China consumed a total of 0.562 billon tons of oil, among which 67.3% was imported from other countries (Tian, 2017). As the energy issues becoming increasingly prominent, safe and stable natural petroleum supplies are of critical importance to China's economic and social development. Underground water-sealed storage has many advantages of less land occupation, higher security, lower cost and more environmental benefits than aboveground storage, which is widely considered as a technically sound and economically feasible storage method. Underground water-sealed storages for crude oil, liquefied petroleum gas (LPG) and liquefied natural gas (LNG) have been developed worldwide since the early twentieth century, for example the LPG storage in the Seto inner-sea area of Japan (Tezuka and Seoka, 2003), the crude-oil storage in Korea (Lee and Song, 2003) and the hydrocarbon storage in the Perama area of Greece (Benardos and Kaliampakos, 2005). In 2003, China began to construct the national strategic oil storage bases. At the Stage II Plan of China since 2008, the seven to eight underground water-sealed depots have been currently in the implementation stage. The four underground water-sealed storage caverns in Huangdao in Shandong Province, Jinzhou in Liaoning Province, Zhanjiang and Huizhou in Guangdong Province have started construction and come into use gradually.

The basic principle of underground oil storage in unlined rock caverns is that groundwater pressure around caverns should be higher than the storage cavern pressure and thus groundwater flows into caverns to prevent oil leakage. The water-sealing effect and rock mass stability are two key problems for the construction of underground storage caverns (Zhuang et al., 2017). Suitable water pressure can be obtained by locating the caverns at a sufficient depth or by installing a water curtain system. When the hydrodynamic containment of storage caverns cannot be maintained by natural groundwater, an artificial water curtain system consisting of galleries and arrays of the drilled holes above the crown of caverns would be needed. Moreover, groundwater flow into a cavern may induce a potential hazard for cavern stability (Sun and Zhao, 2010). Wang et al. (2015) investigated the design and testing of water curtain systems in detail. The seepage field analysis of underground water-sealed storage have also been conducted using numerical simulations by many researchers (Sun and Zhao, 2010; Sun et al., 2011; Yu et al., 2013; Lin et al., 2016; Li et al., 2017). Among them, Lin et al. (2016) developed a transient unified pipe network method to evaluate the water-sealing effectiveness and Li et al. (2017) presented a three-dimensional numerical method for seepage analysis of the water-sealed oil storage caverns considering the spatial effect of

* Corresponding author.
E-mail address: zhaoxingdong@mail.neu.edu.cn (X.-D. Zhao).

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water curtain boreholes and the influence of oil vapor. Although underground water-sealed storage caverns are generally constructed within hard rock masses, these cavern are characterized by large-cross-section, multiply excavation faces, uncertain discontinuities and long term effect by a dynamic groundwater seepage, which determines that underground oil storage caverns have a lot of differences with other underground constructions. The stability of storage caverns is one of the key requirements during construction and operation stages. Many studies have been conducted on the stability of underground storage caverns using numerical methods and in-situ testing and monitoring. Lee et al. (1997) studied the behavior of oil-storage caverns during excavation based on the instrumentation measurements and numerical analysis. Chen et al. (2013) solved the hydro-mechanical problem for underground oil storage caverns using discontinuous deformation analysis. Aiming at the Huangdao project in China, Wang et al. (2013) studied the influences of construction sequence on the hydro-mechanical behavior using Finite Element Method (FEM); Li et al. (2014) analyzed the hydro-mechanical behavior using Discrete Element Method (DEM); Qiao et al. (2016) systematically presented the geotechnical monitoring. For the Jinzhou project in China, Ma et al. (2016) evaluated the stability and damage mechanism of underground caverns by integrating Continuous-Discontinuous Element Method (CDEM) and microseismic monitoring. On this basis, Zhuang et al. (2017) investigated the temporal-spatial evolution of the micro-cracks and energy-release patterns induced by excavation unloading. The above studies provide valuable engineering references for constructing an underground oil-storage facility. However, studies involving the detail support design of the storage caverns have seldom reported.

To determinate reasonable support systems is crucial to ensure projects to be carried out economically, safely and successfully. There are many influence factors on stability of storage caverns, such as geology, hydrogeological characteristics and mechanical properties of rock masses, and some of these factors are difficult to monitor during construction. Therefore, it would be improper to simply use the experience in support design. The Geomechanics Classification or the Rock Mass Rating (RMR) (Bieniawski, 1989), Rock Mass Quality (*Q*) (Barton, 2002) and Geological Strength Index (GSI) (Marinos and Hoek, 2000) classifications are the most widely used empirical methods, which are preferred by rock engineers and have gained a universal acceptance. However, these empirical methods cannot provide the stress and displacement information. Therefore, in this study, the numerical analysis of support systems obtained from empirical rock mass classifications are used to evaluate the support system based on an underground water-sealed oil storage facility in China. The groundwater flow is also considered in the numerical analysis.

2. Project overview

2.1. Design and construction

The Jinzhou national oil storage project is located in Liaoning Province, the northeast area of China. The geomorphic unit belongs to a hilly region and the elevation of the ground level ranges from 12.70 m to 42.83 m ACD (where ACD is the abbreviation of Admiralty Chart Datum). The design storage capacity of the project is $3 \times 10^6\ m^3$ for crude oil. Fig. 1 shows the layout of the underground facility, which is located more than 100 m below the ground surface. The underground facility is composed of four groups of storage caverns (each group consists of two connected caverns), four inlet oil shafts with a diameter of 3 m, four outlet oil shafts with a diameter of 6 m, two access tunnels and an artificial water curtain system. The eight storage caverns, namely 1N-4N and 1S-4S, are parallel to one another, aligned in the East-West direction. Two storage caverns for each group are connected by horizontal tunnels in order to guarantee the same liquid level. During the operation stage, the connection tunnels between the groups will be separated by concrete sealing plugs and thus each group can form an independent oil storage unit. The oil inside every storage group is sealed by the horizontal and vertical water curtain holes drilled from the water curtain tunnels.

Fig. 2 shows the cross-section view of the project. Two horseshoe-shaped access tunnels are 8 m wide and 8 m high. Every storage cavern is 19 m wide, 24 m high and 934 m long, and the cross-section shape is three-center arched roof and straight wall. The distance between the adjacent caverns is 38 m. The floor level of the storage caverns is at an elevation of −80 m. The water curtain tunnels, which are also arched, are 6.5 m wide, 6 m high and 974 m long. The floor elevation of water curtain tunnels is −32 m and the horizontal water curtain system is installed 25 m above the storage caverns. The vertical water curtain holes extend 10 m beyond the cavern floor. The diameter of the water curtain boles is 100 mm and the spaces of the horizontal and vertical holes are 10 m and 20 m, respectively. The tunnels and caverns are excavated using the drill-and-blast method. For the large-cross-section caverns, these caverns are excavated in three equal height sections (top heading, bench-1 and bench-2), each of which is 8 m high.

2.2. Geology and hydrogeology

There are no active and regional faults near the project area. Some inactive faults exist in near-field region and these faults extend mainly in three directions: SN, NE and NW. Based on core logging data, the strata at the project area are divided into the residual soil layer, the completely weathered layer, the strong weathered layer, the moderately weathered layer, the slightly weathered layer and the unweathered layer according to the weathering and integrity levels of rock masses. The bedrock at the area consists mainly of metamorphic of Archeozoic period and intrusive rock. The predominant rock types are reddish-gray, medium-coarse grained granites interpenetrated by diabase, amphibole dioritic porphyrite and aplite. According to the evaluation of *Q*-system for exploration boreholes, the *Q*-values are generally greater than 10 (see Table 1) and the rock mass quality is very good at the proposed cavern location (El. −20 m to −80 m). Thus, the excellent rock conditions are very suitable for the cavern construction.

Underground water consists of Quaternary pore water and bedrock fissure water. Generally, the underground water flow direction is southwest and water table is at about 13.33–38.31 m below ground surface, which has an annual variation of 1–3 m. The type of hydrochemistry is sodium bicarbonate calcium chloride. The PH value is between 6.68 and 9.15. Water salinity is 138.14–232.37 mg/L. The water quality is good. The results of comprehensive hydraulic pressure tests show that the permeability coefficient is mainly less than 1.00×10^{-10} m/s, and ranging from 1.55×10^{-9} to 3.50×10^{-7} m/s (the mean value is 5.83×10^{-8} m/s) at fractured zones.

The in-situ stress measurements indicate that in the buried depth of caverns the maximum principal stress is 6.19–11.5 MPa with a direction N71.7°-78.5 °E; the middle principal stress is 3.63–9.02 MPa in the horizontal plane; and the minimum principal stress is about 1.81–3.61 MPa in the vertical direction.

3. Field and laboratory studies

The field and laboratory studies include field observation, boreholes and discontinuity survey and laboratory testing. The study region for the field investigation is the cavern 4N and three sites (the mileage locations: 4 + 05-4 + 30 m for site #1, 3 + 20-3 + 30 m for site #2 and 0 + 70-1 + 50 m for site #3) were selected according to the variations of discontinuities (see Fig. 3). ShapeMetrix3D photogrammetric measurement system (Liu et al., 2017) was adopted for the discontinuity survey of three sites. The discontinuity information was obtained from the wall surface exposures. Fig. 4 shows the identification effect for field discontinuities of site #1 with the size 9.5 m × 3.8 m, showing three discontinuity sets. The statistical data of discontinuity parameters obtained from all sites are given in Table 2.