Tunnelling and Underground Space Technology 40 (2014) 75–84

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

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

Discrete element analysis of hydro-mechanical behavior of a pilot underground crude oil storage facility in granite in China

Shucai Li, Zhechao Wang *, Yang Ping, Yi Zhou, Li Zhang

Geotechnical and Structural Engineering Research Center, Shandong University, Jinan, Shandong 250061, China

ARTICLE INFO

Article history:
Received 25 May 2013
Received in revised form 10 September 2013
Accepted 26 September 2013
Available online 16 October 2013

Keywords:
Fracture rock mass
Hydro-mechanical coupling
Discrete element method
Underground storage caverns
Water curtain
Back analysis

ABSTRACT

The hydro-mechanical behavior of a pilot underground crude oil storage facility in granite in China is analyzed using Discrete Element Method (DEM). Characterization of hydro-mechanical coupling behavior of rock mass was performed using geological investigation, laboratory test, field monitoring and case study. Geological investigations were performed to obtain the geometrical properties of joints. Direct shear tests were performed to obtain the mechanical behavior of joints. A case study was performed to obtain the hydro-mechanical parameters of rock mass around the facility. Discrete element method was employed to assess the hydro-mechanical behavior of the facility. The groundwater pressure distribution and flow rate of the facility under different water curtain pressures were obtained. The groundwater inflow, deformation and stability of the caverns were obtained through the numerical simulations. It was found that the water seal property could not maintain if there is no water curtain system for the facility. The groundwater flow rate increases with the water curtain pressure. Both groundwater flow rate and crown settlement from this study are comparable to those from field measurements. However, the simulated flow rate and crown settlement are less than those predicted using empirical equations, due to the interaction between neighboring caverns and the effect of groundwater table dropdown.

1. Introduction

The demand for natural carbonate resources is increasing all over the world. Safe and stable natural carbonate resource supply is of critical importance for most of countries to fuel their economic and social developments. Storage of these carbonate resources often provides an economic way to secure the supply. One of the technically sound and economically feasible solutions for the storage is to construct underground storage facilities. Underground storage takes advantages over ground surface storage in terms of safety, environment and economy. The carbonate resources could be underground stored in the state of liquefied petroleum gas (Goodall et al., 1988), gas (Liang and Lindblom, 1994; Lu, 1998; Yang and Guan, 2001; Kim et al., 2007), or crude oil (Shi and Liu, 2010).

The basic principle of underground storage is that the groundwater pressure around the caverns should be higher than the pressure of stored gas, liquefied petroleum gas, or crude oil to prevent leakage toward the surrounding rock mass. Aberg (1977) investigated the relation between water curtain pressure and storage pressure in caverns. Through the investigation, he indicated that if the vertical hydraulic gradient is higher than one, the stored petroleum gas would not leak through the rock mass around the caverns. Goodall et al. (1988) insisted that no leakage will occur as long as the water pressures increases along all possible escape paths. Liang and Lindblom (1994) investigated the influences of different factors on gas storage capacity. They indicated that the critical pressure for a gas storage facility is considerably less than both the natural hydrostatic and the applied water curtain pressure.

The technique of underground storage with water curtain system has been widely adopted worldwide. Kiyoyama (1990) introduced the state of art for the underground crude oil storage technology in Japan. Hoshino (1993) presented a geological stability study for the construction of underground caverns for petroleum storage in orogenic areas. Lee et al. (1996) introduced the design and construction aspects of unlined oil storage caverns in rock. Benardos and Kaliampakos (2005) presented the Greek experience for the construction of unlined oil storage caverns in limestone formations. Park et al. (2005) presented the geo-engineering problems and approaches in the design of a LPG storage terminal underneath a lake. All the above studies provide valuable engineering experiences in the design and construction of underground storage facility.

In the case of crude oil storage, the bedrock is usually dominated by crystalline hard rocks. In this case, the performance of the storage caverns depends greatly on the hydro-mechanical

---

* Corresponding author. Address: Geotechnical and Structural Research Center, Shandong University, #17923, Jingshi Road, Jinan, Shandong 250061, China. Tel.: +86 531 88399712; fax: +86 531 88395984.

E-mail address: wanz@sdu.edu.cn (Z. Wang).

0886-7798/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.tust.2013.09.010

property of rock mass. One of the important issues in the design and construction of underground unlined caverns is to assess their water seal and stability behavior. Lu (1998) performed a finite element analysis to evaluate its stability. Discrete element method was employed to investigate the influence of stress-permeability coupling on water inflow into excavation (Mas Ivars, 2006). It was found that stress-permeability coupling is one of the causes for the usually less than expected flow rate into drillholes. Kim et al. (2007) investigated the influence of spatial variability of hydraulic conductivity on the critical hydraulic gradient for gas containment of underground storage caverns. Wang et al. (2013) investigated the influences of construction sequence on the hydro-mechanical behavior of an underground crude oil storage cavern facility using finite element method.

In China, an underground crude oil storage facility, which is one of the first unlined crude oil storage facilities in crystalline hard rocks, is being constructed in granite to meet the fluctuant need of carbonate fuels in that area. It is of importance to assess the hydro-mechanical coupling performance of the underground crude oil storage caverns, including the groundwater drawdown and stability of rock mass around caverns. For granitic rock mass, the influence of joint on the hydro-mechanical behavior is pronounced. Therefore, in this study the hydro-mechanical behavior is assessed using discrete element method with the emphasis on the consideration of joints in rock mass. The geological investigations were performed to obtain the geometrical properties of joints. The direct shear tests were performed to obtain the mechanical behavior of joints. A case study was performed to obtain the hydro-mechanical parameters. Discrete element method was employed to assess the hydro-mechanical behavior of the facility. In the analysis, the groundwater pressure distribution and flow rate under different water curtain pressures were obtained. The groundwater inflow, deformation and stability of the caverns were estimated using simulation results.

2. Discrete element analysis of hydro-mechanical coupling effect

The objective of this study was to investigate the hydro-mechanical behavior of an underground crude oil storage facility in granite, so as to evaluate the groundwater seal effect and stability behavior. When an underground excavation is made, there is first stress redistribution around the excavation, which will in turn change the local joint aperture. The change in joint aperture induces the changes in permeability of the rock mass and thereby groundwater pressure distribution around the excavation. And at the same time, the change in groundwater pressure will alter the stress distribution. Several critical aspects on discrete element analysis of hydro-mechanical coupling effect will be introduced in the following section. More details on the theory of coupled pore pressure/stress analysis could be found in the references (Mas Ivars, 2006). In this study the coupled problem was solved using a commercial code, UDEC (Itasca Inc., 2000).

2.1. Fluid flow through joint

Flow in planar rock joints may be idealized by means of the parallel plate model, and the analytic solution for laminar viscous flow between parallel plates gives the fluid rate as (Witherspoon et al., 1980).

$$q = -k_j a_h^3 \frac{\Delta p}{l} \tag{1}$$

in which, q is the flow rate through a joint, k_j is a joint permeability factor, l is the joint length, Δp is the pressure difference along the joint length, and a_h is the equivalent hydraulic aperture.

As the permeability of rock mass decreased with saturation degree, a factor is multiplied into Eq. (1) to account for the influence of saturation degree. The factor is a function of saturation and expressed as (Itasca Inc., 2000):

$$f_s = s^2(3 - 2s) \tag{2}$$

where f_s is the factor accounting for saturation effect, and s is saturation degree.

2.2. Barton–Bandis model

Barton–Bandis model was developed to describe the nonlinear shear stress–shear displacement relation for joints. In the model, the shear strength is formulated as a function of normal stress, friction angle of joint and joint roughness coefficient. The shear strength is expressed as (Barton et al., 1985):

$$\tau = \sigma_n \tan\left[\phi_b + JRC \lg_{10}\left(\frac{JCS}{\sigma_n}\right)\right] \tag{3}$$

where τ is shear strength of joint, σ_n is normal stress applied to joint, ϕ_b is the friction angle of joint, JRC is joint roughness coefficient, and JCS is joint wall compression strength.

The normal stress-displacement relation in the model was described as (Barton et al., 1985):

$$\sigma_n = \frac{-u_{nc} \cdot K_{ni}}{1 - u_{nc}/\upsilon_{mi}} \tag{4}$$

where u_{nc} is the current normal displacement, K_{ni} is the initial normal stiffness, and υ_{mi} is the maximum allowable closure.

2.3. Hydro-mechanical coupling

In hydro-mechanical coupling analysis, the equivalent hydraulic aperture in Eq. (1) is determined according to the joint aperture at zero normal stress, and the joint normal displacement, as shown in the following equation (Itasca Inc., 2000):

$$e = e_0 + u_n \tag{5}$$

where e_0 is initial equivalent hydraulic aperture and u_n is joint normal displacement. The variation of joint normal displacement with normal stress on the joint could be described using mechanical models for joints, i.e., Eq. (4).

The influence of fluid flow on mechanical behavior is accomplished through fluid pressure. The fluid pressure on joint is expressed as (Itasca Inc., 2000):

$$F_i = p n_i L d \tag{6}$$

in which,

$$p = p_0 + K_w Q \frac{\Delta t}{V} - K_w \frac{\Delta V}{V_m} \tag{7}$$

In the above equations, F_i is the pressure on joint exerted by fluid, d is width of block intersected by joints, n_i is the unit normal vector of joint surface, L is the length of joint, p_0 is the initial fluid pressure, K_w is the fluid volumetric deformation modulus, Q is the sum of flow rates into the domain from all surrounding contacts, ΔV is the increment in fluid volume, V is the fluid volume after deformation, V_m is the fluid volume before deformation, and Δt is the time step increment. In Eq. (7), the first, second and third term represent the initial fluid pressure, the pressure induced by flow into the domain, and the pressure induced by compressibility of joint wall. In this manner, the mechanical behavior of joint is related to the fluid flow through joints.