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Stability analysis of underground oil storage caverns by an integrated numerical and microseismic monitoring approach

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ABSTRACT

Underground storage in unlined caverns is of great significance for storing energy resources. Construction of underground storage caverns is an extremely complex process, involving extensive multi-bench excavation and strong unloading. Excavation-induced damage of surrounding rock masses may lead to instability of underground storage caverns. The aim of this paper is to put forward a method by integrating numerical simulation and microseismic monitoring for evaluation of cavern stability. A novel numerical method called Continuous–Discontinuous Element Method (CDEM) is applied to simulate micro-cracks under excavation-induced unloading conditions. Meanwhile, a microseismic (MS) monitoring system is employed to monitor real-time MS events during construction of storage caverns. Numerical results are validated using the monitoring data from the MS monitoring system. The integrated method is proved to be successful in capturing micro-cracks in underground storage caverns. Local instability, potential unstable zones and micro-crack evolution are analyzed, and cracking mechanisms are also discussed.

1. Introduction

Underground storage in unlined caverns has numerous advantages over aboveground storage (Morfeldt, 1974; Bergman, 1984; Broms and Zhao, 1993; Zhao et al., 1996, 1999, 2004; Sun and Zhao, 2010; Rutqvist et al., 2012), for instance, larger storage capacity, longer service life, and less resource consumption. Meanwhile, the underground storage is safe from extreme conditions such as fire, earthquake and explosion. For oil storage caverns, the sealing effects of groundwater reduce the risk of oil leakage toward the surrounding rock mass (Kiyoyama, 1990). Therefore, underground storage caverns have been popular in various countries for storing strategic energy resources (Morfeldt, 1983; Kiyoyama, 1990; Lee and Song, 2003; Benardos and Kaliampakos, 2005; Li et al., 2014), including crude oil (Kiyoyama, 1990), liquefied petroleum gas (LPG) (Yang and Guan, 2001) or liquefied natural gas (LNG) (Lee et al., 2006). Whichever kind of energy resources are stored in the underground storage caverns, two fundamental principles should be strictly followed. The first one is that the groundwater pressure around caverns should be higher than that of the stored energy resource so as to prevent its migration (Åberg, 1977; Thunvik and Braester, 1980; Goodall et al., 1988; Lindblom, 1997; Yang et al., 2004; Sun and Zhao, 2010; Sun et al., 2011; Li et al., 2014). The other is the stability of rock masses around caverns (Lindblom, 1997; Lu, 1998; Ibrahim et al., 2015).

However, high sidewalls and large spans of caverns, and uncertain discontinuities in the surrounding rock masses are often encountered, which seriously threaten the stability of underground caverns (e.g., Zhu and Zhao, 2004; Zhu et al., 2010). Many studies have been conducted on the stability of underground storage caverns during the construction phase. Gnirk and Fossum (1979) established a numerical model for the assessment of cavern stability of compressed air energy storages using probabilistic design procedures. Lindblom (1997) addressed rock stability by developing criteria to ascertain the full operation integrity of underground caverns. Tezuka and Seoka (2003) analyzed the stability of the surrounding rock masses of large-cross-section underground oil storage caverns in earthquake-prone Japan. Park et al. (2005) carried out geophysical investigations and numerical analyses for the stability assessment of the first LPG storage terminal constructed underneath a lake in western Korea. Yang et al. (2014) investigated the anisotropic properties of rock masses with consideration of the seepage-stress coupling effect. Nevertheless, there is no universal

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understanding on the stability mechanism of underground storage caverns due to uncertainties on geological structures and rock properties. With gradual expansion of underground storage caverns, the stability of surrounding rock masses during excavation becomes the key to the success of an underground storage cavern project. The unloading effect during excavation has great impact on the stability of underground storage caverns. Thus, integrated methods are necessary to analyze the stability and damage mechanism of underground storage caverns during construction. Continuous numerical approaches, such as finite difference method (FDM) (Narasimhan and Witherspoon, 1976), finite element method (FEM) (Koyama et al., 2009) and Boundary Element Method (BEM) (Mohanty and Vandergrift, 2012) have been extensively applied for stability analysis for underground storage caverns to deal with continuum-based problems (e.g. Preece and Foley, 1983; Lu, 1998; Heusermann et al., 2003; Mandal et al., 2013; Wang et al., 2015b). Discontinuous methods, for instance, discrete element method (DEM) (Cundall, 1971; Cundall and Strack, 1979), and discontinuous deformation analysis (DDA) (Shi, 1988), are useful to analyze discontinuities of rock masses (e.g. Zhao et al., 1999; Nadimi et al., 2011; Chen et al., 2013; Li et al., 2014; He and Zhang, 2015). However, studies involving the damage and failure evolution of the surrounding rock masses of the storage caverns have seldom reported. A motivation is to combine advantages of both continuous and discontinuous approaches proposed by Munjiza et al. (1995), Li et al. (2004), Wang et al. (2013), etc. These combined methods include FDEM (FEMDEM) (Munjiza et al., 1995; Munjiza, 2004; Mahabadi et al., 2010, 2012; Lisjak et al., 2014, 2015) and Continuous–Discontinuous Element Method (CDEM) (Li et al., 2004, 2008; Ma et al., 2011; Wang et al., 2013; Li et al., 2015). In the study of Cai et al. (2007), the continuum-based software FLAC was coupled with the discontinuum-based software PFC to investigate acoustic emissions in large-scale underground excavations. Lisjak et al. (2015) used the FDEM method to model the crack evolution due to the excavation of a circular tunnel in a bedded argillaceous rock. The progressive failure of rock masses was simulated by a cohesive-zone approach (Munjiza et al., 1995; Munjiza, 2004; Mahabadi et al., 2010, 2012; Lisjak et al., 2014, 2015). The method of CDEM not only can deal with both continuous and discontinuous problems, but also can reproduce the progressive damage and failure evolution of materials from a continuous state to a discontinuous state (Li et al., 2015). In the present study, CDEM is employed to simulate the excavation process of underground storage caverns.

Microseismic (MS) monitoring techniques have been successfully used to accurately and effectively monitor the micro-cracks within surrounding rock masses in many engineering projects (e.g., Hong et al., 2006; Kaiser, 2009; Tang et al., 2011; Xu et al., 2011; Ma et al., 2013; Cai et al., 2015; Feng et al., 2015, 2016). In this study, an advanced Microseismic Monitoring System (Engineering Seismology Group, Canada) is applied, which consists of microseismic sensors installed in rock masses, a Paladin data acquisition system and a data analysis center. Meanwhile, MS monitoring are used to verify CDEM results.

In this paper, two adjacent oil storage caverns are investigated to understand damage mechanisms of surrounding rock masses during the construction phase. The main objectives include modeling the damage process of the surrounding rock masses, validating CDEM results by M monitoring data, and analyzing the stability of underground storage caverns.

2. Project overview

2.1. Project layout

An underground water-sealed storage cavern project is selected for stability analysis with an integrated numerical and MS monitoring method. This project located in Jinzhou, Liaoning Province, China, was designed to have a total capacity of $300 \times 10^4\,m^3$ for crude oil. It consists of eight storage caverns, namely 1N–4N and 1S–4S (see Fig. 1), which are located more than 100 m below the ground surface. The top of the caverns is located at −53 m ACD, and the bottom at −76 m ACD (where m stands for meter and ACD is the abbreviation of Admiralty Chart Datum). The cross section of each cavern has a dimension of 19 m in width and 24 m in height. The caverns are 946 m long along the East-West axis. The distance between two adjacent caverns is 48 m. In this paper, the construction process of 1N and 1S oil storage caverns is studied to analyze the damage mechanism of surrounding rock masses and thus to evaluate the stability of caverns.

2.2. Engineering geology

The ground surface is covered by residual soil while the bedrock consists of coarse and medium grained granite, according to site investigation and lab experiments. There are no large-scale fractures found within 10 km from the site. However, there are some diabase, aplite and diorite dikes (see Fig. 2), trending mainly in

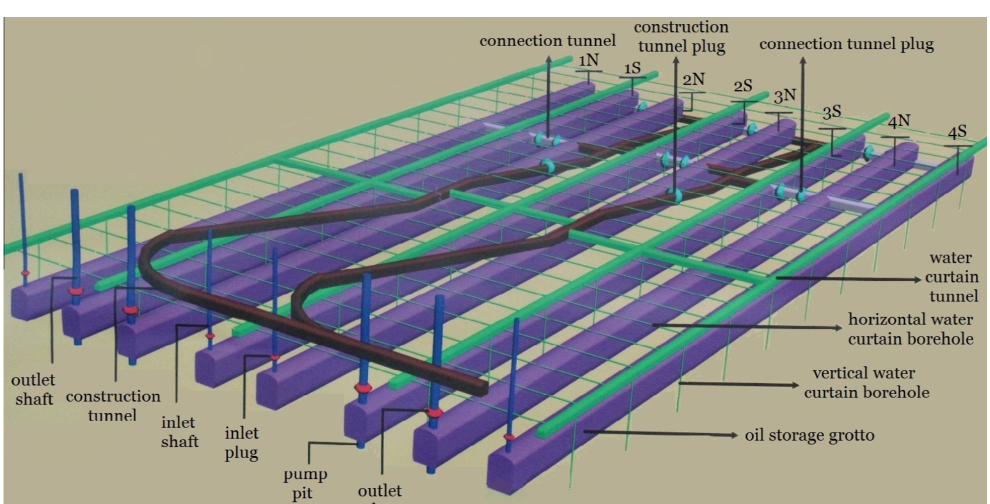

Fig. 1. Layout of the Jinzhou water-sealed underground storage caverns project.