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Effects of excavation unloading on the energy-release patterns and stability of underground water-sealed oil storage caverns

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ABSTRACT

Large-scale underground water-sealed oil storage caverns have become an important method for storing strategic crude oil reserves worldwide. Previous studies have focused on the stability of the surrounding rock masses during excavation processes. In this study, a microseismic monitoring system was installed in the 1N and 1S Oil Storage Grottos (OSGs) of the Jinzhou underground water-sealed oil storage caverns. The major goals of this study were to investigate the temporal-spatial evolution of the micro-cracks and energy-release patterns induced by excavation unloading in surrounding rock masses. The measured waveforms were interpreted via the time-frequency combined analysis method. The results show that the excavation blasting damage range in the Jinzhou underground storage caverns was about 120 m. The local instability phenomena (e.g., "cavity collapses") occurred in the vicinity of a mileage location of 2 + 45–2 + 55 m in the southern sidewall of the middle layer of the 1N OSG due to the energy-release in the surrounding rock masses resulting from excavation unloading. Excavation unloading induced the formation and localization of micro-cracks, which eventually produced local rock failure. Also, the energy-release patterns in the surrounding rock masses and the relationship between stability and those are revealed, providing a reference for identifying, delineating and predicting potential danger areas in the surrounding rock masses for underground water-sealed oil storage caverns.

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1. Introduction

Due to certain advantages, such as large storage capacities, high degrees of safety, sound emergency response capability, long service lives, low costs and economical land resource usage (Zhao et al., 1996), underground water-sealed storage caverns have become the primary method for storing energy resources (e.g., oil, gas). To strengthen the ability to manage potential interruptions to petroleum distribution, the second and third phases of national oil reserve projects have been constructed in succession with a reserve scale equivalent to the net petroleum import volume of 60 days in China since 2008.

Large-scale underground water-sealed oil storage caverns are often unlined rock caverns with high sidewalls and large spans that are constructed and operated in a dynamic groundwater environment over a long period of time. The water-sealing effect and rock mass stability are key requirements for the construction of oil-storage caverns. Extensive studies of these two key issues have been conducted worldwide (Aberg, 1977; Yang and Kim, 1998; Benardos and Kaliampakos, 2005; Sun and Zhao, 2010; Goel et al., 2012), particularly on the water-sealing techniques widely used in engineering practices (Park et al., 2005; Sun et al., 2011; Yu et al., 2013; S.C. Li et al., 2014). However, because the surrounding rock masses are affected by pressurized oil, gas and water, the stability analysis for such rock caverns during construction and operation phases are typically complex. Various methods, including the finite element method, the back analysis method and the block theory (Lee and Song, 2003) have been used in detailed studies of the time-dependent behaviors, deformation characteristics and long-term stability of underground water-sealed storage caverns (Tezuka and Seoka, 2003; Mohanty and Vandergrift, 2012). Moreover, Chen et al. (2016) developed a coupled hydro-mechanical model based on discontinuous deformation analysis method to investigate the stability of the underground caverns. Wang et al. (2015a,b) assessed the hydro-mechanical behavior of the surrounding rock masses subjected to different stress paths during its excavation and cyclic loading during its operation using finite element method. These studies described the mechanical or hydro-mechanical responses of the surrounding rock masses

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during construction and operation. However, these studies were based on theoretical and numerical analyses of generalized models that could not describe the stress and deformation response mechanism in detail due to large cavern spans, intersecting caverns, multiple working faces, intensive excavation unloading and a strong dependence on engineering geology. Thus, a stability analysis method that uses in-situ testing and monitoring would be practical and have many applications.

When a rock mass experiences external loading, it either absorbs external energy (e.g., mechanical energy, thermal energy) and converts it into internal energy or releases its internal strain energy in some way until it fails. This describes an energy-driven destabilization phenomenon (Xie et al., 2009). Energy-release can be a suitable index for evaluating the stability of rock mass structures, including underground storage caverns. In recent years, the Microseismic Monitoring System (MMS), which is a 3D monitoring technology, has been used to accurately and effectively detect the micro-cracks in rock masses to reveal the energy-release patterns of rock masses under external disturbance (Xu et al., 2011). To study the initiation, evolution and energy-release patterns of micro-cracks with the goal of predicting the stability of rock masses, the MMS has been applied to many engineering projects, including mines (Wang and Ge, 2008; Kaiser, 2009); high and steep slopes of hydropower stations (Xu et al., 2011); tunnels (Hirata et al., 2007; Tang et al., 2011); hot dry rock power-generation systems (Tezuka and Niitsuma, 2000); and underground powerhouses (Xu et al., 2015; Dai et al., 2016). Hong et al. (2006) preliminarily analyzed the formation mechanism of micro-cracks in areas damaged by blasts and provided an empirical evaluation standard for evaluating the stability of rock masses around an underground oil-storage cavern using microseismic monitoring results, which have demonstrated the feasibility of MMS. Indeed, MMS provides an effective method to track microseismic energy-release which is different from the actual energy-release of the rock masses. Since some parameters (e.g., seismic efficiency (Xu et al., 2014)) are proposed in rock engineering to transform microseismic energy-release into actual energy-release of the rock mass, it is reasonable that the microseismic energy-release patterns of rock masses during excavation represent the actual energy-release patterns of surrounding rock masses induced by excavation unloading and can be utilized to investigate the energy evolution of the rock masses in the underground storage caverns.

In this study, a microseismic monitoring system was established in the 1N and 1S Oil Storage Grottos (OSGs) of the Jinzhou underground water-sealed oil storage caverns. The evolution patterns of micro-cracks in the surrounding rock masses induced by excavation unloading were also monitored and analyzed in real-time and the relationship between the energy-release patterns and stability of the surrounding rock masses was described. The potential danger areas in the surrounding rock masses were also identified and delineated to describe the conditions and essential failure characteristics of the surrounding rock masses during excavation.

2. Underground caverns and excavation schedule

2.1. Project description

The Jinzhou underground water-sealed oil storage caverns are located in Liaoning Province in the northeast region of China. The surface elevation of the project area is 15–43 m ACD (where m stands for meter and ACD is the abbreviation of Admiralty Chart Datum), and the groundwater level is 10–25 m beneath the surface. The storage caverns have a total design capacity of $300 \times 10^4\ m^3$. The oil-storage facilities in the underground caverns primarily consist of 8 OSGs, a water curtain system, construction tunnels and access tunnels (Fig. 1). Each of the OSGs arranged in parallel in an east-west direction is 19 m wide at the base with a bottom elevation of −76 m ACD, 24 m tall and 934 m long (Lin

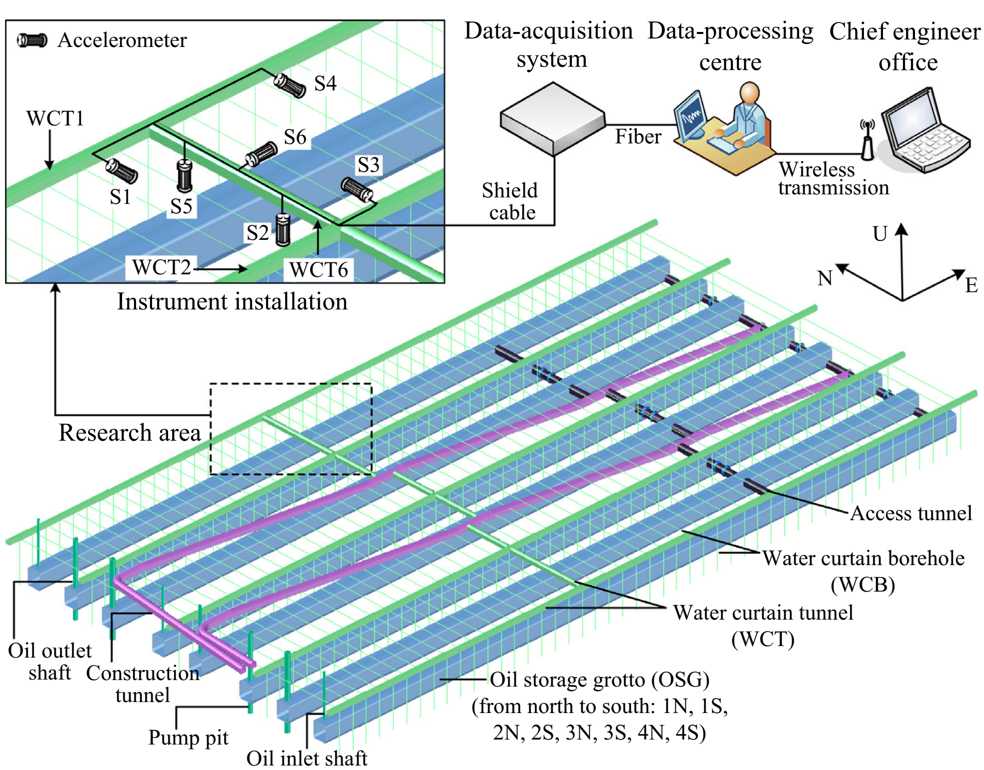

Fig. 1. Topological graph of the microseismic monitoring system (MMS) of the Jinzhou underground water-sealed oil storage caverns.

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