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Dynamic response of underground gas storage salt cavern under seismic loads

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A B S T R A C T

A dynamic elastoplastic damage constitutive model is proposed based on the failure characteristic of rock salt under seismic loads. The coding of the proposed model is achieved by the embedded FISH (short for FLACish) language of $FLAC^{3D}$ (Fast Lagrangian Analysis of Continua). Numerical models of bedded salt cavern gas storage facilities in China are developed by using $FLAC^{3D}$, and the proposed constitutive model is used in the simulations. The effects of seismic input angle, seismic acceleration, seismic moment, types of seismic waves, and gas pressure on the dynamic response, stress, displacement, plastic zone, and safety factor (SF) of rock masses that surround salt cavern gas storage facilities are studied. Results show that the seismic wave perpendicular to the surface poses the greatest risk to the safety of the cavern. With an increase in seismic acceleration, the cavern's SF decreases and that of the lower structure of the cavern decreases more than that of the upper section. Plastic zones propagate from the cavern's internal surface to the pillar, and then to the pillar and floor along the right and left corners of the cavern bottom. Higher internal gas pressure improves cavern safety. The acceleration and duration of seismic waves are critical factors in ensuring the safety of the cavern. The SF of the cavern's lower structure is more sensitive to changes in seismic parameters than that of the other locations, which makes the cavern bottom more likely to be destroyed during an earthquake. Therefore, the lower structure should be the study target in the seismic design for a salt cavern gas storage facility. Results have been used in the seismic design of salt cavern gas storage facilities in China.

1. Introduction

Natural gas is the most environmentally friendly fossil fuel because its combustion generates the lowest CO_2 emissions. In addition, it is available in larger quantities than crude oil. Therefore, it is increasingly replacing crude oil as one of the main energy sources in China. Notwithstanding limited domestic gas production, natural gas consumption has increased significantly, thereby increasing China's dependency on natural gas imports. This in turn increases the importance of natural gas storage to ensure supply security. Underground salt caverns are considered the most suitable storage facilities for natural gas because of their capacity for fast delivery and ability to quickly switch from injection to production (Nazary et al., 2013; Mortazavi and Molladavoodi, 2012; Wang et al., 2013, 2012, 2011; Niklas et al., 2012). Therefore, underground salt cavern gas storage facilities have become one of the hot topics in engineering in China.

Fig. 1 presents the depths, shapes, and relative volumes of typical salt cavern gas storage facilities in the world (John, 2006). Such facilities are characterized by wide depth distribution (from a few hundred to more than two thousand meters), different shapes, massive volume (typically several hundred thousand to over one million cubic meters), and locations in complex geological formations. These characteristics make salt cavern gas storage facilities vulnerable to earthquakes. Once the cavern fails during an earthquake, high pressure and escaping natural gas can cause fires and explosions. Therefore, studies on the dynamic response and safety evaluation of salt cavern gas storage facilities under seismic loads are necessary.

Earthquakes can trigger additional geological disasters. Structures are subjected to excessive loads in an instant, thereby damaging surface and underground structures, and causing such structures to fail. However, more studies focus on the effects of earthquakes on surface structures, such as buildings, pipelines, and dams, than on underground structures. This is due to the fact

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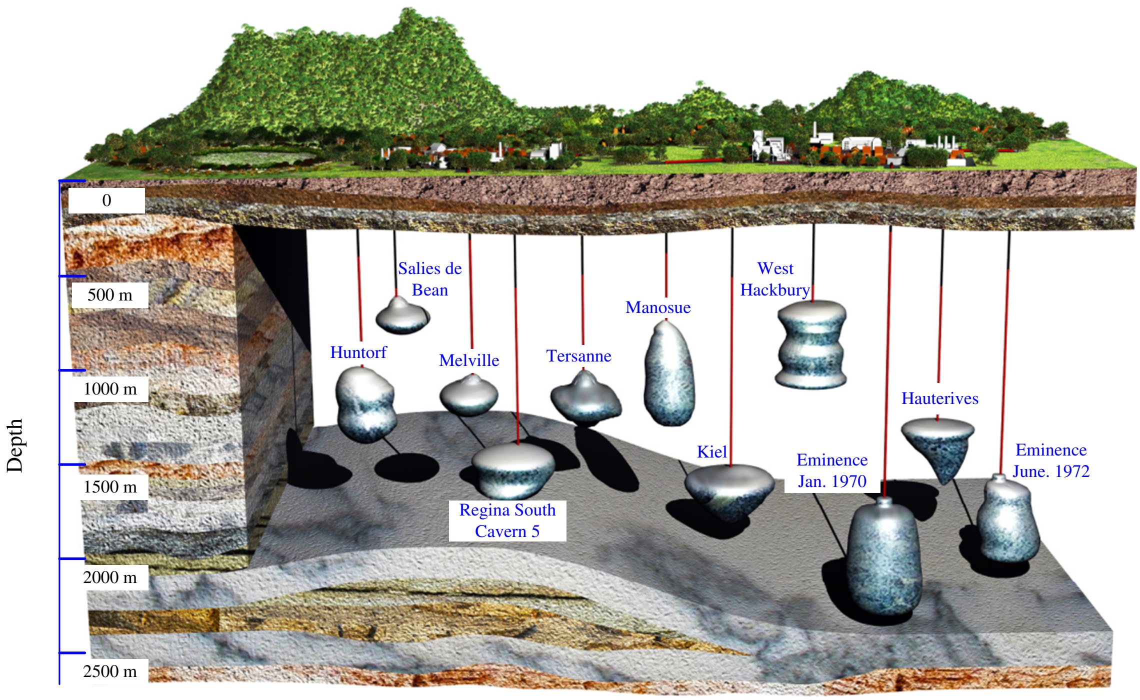

Fig. 1. Depths, shapes, and relative volumes of typical salt cavern gas storage facilities around the world (modified from John, 2006).

that failures of and damages to surface structures are more easily observable than those of underground structures, especially when the underground structure is very deep. However, some recent earthquakes, such as those that took place in 1995 in Kobe, Japan, in 1999 in Chi-Chi, Taiwan, in 1999 in Kocaeli, Turkey, in 2008 in Wenchuan, China, and in 2011 in Yushu, China, have seriously damaged underground structures (Iida et al., 1999; Hashash et al., 2001; Fahimifar and Vakilzadeh, 2009; Chen et al., 2012), thereby prompting engineers to pay more attention to the seismic designs of underground structures.

Existing studies about underground structures under seismic loads mainly focus on tunnels, underground powerhouse caverns, subways, and underground oil and gas pipelines. For example, Dowding and Roten (1978) investigated the failure of tunnels under seismic loads and stated that earthquakes affect a tunnel in three ways: surface soil liquefaction and landslides, large fault displacement, and vibration (dynamic response of the tunnel). Zhu et al. (2011, 2012), Zhu and Zhao (2013) studied the effects of normally and obliquely incident waves on joints and pointed out that joints had a notable influences on the energy transmitted by the seismic waves. Li (2013) and Li et al. (2013, 2014) proposed the thin-layer interface model to study seismic wave propagation normally normal to a filled joint and discussed the effect of the incident angle, the ray path derivation, and some other parameters on the vibration response of underground structures. Their results showed that oblique seismic waves dramatically influenced the dynamic response of an underground rock cavern group. Takashi and Norikazu (1996) investigated the failure of a subway in Kobe during the 1995 Hyogo-ken Nambu earthquake and conducted corresponding numerical simulations. The results indicated that the maximum shear stress reached almost twice the limit shear strength of the rock masses that surrounded the subway. Takashi and Norikazu thought that the shear stress produced by the earthquake was the critical factor that caused the failure of the subway's intermediate pillar. Davis and Bardet (2000) conducted field investigations on 61 corrugated metal pipes shaken by the 1994 Northridge earthquake. They found that 28 of the small-diameter corrugated metal pipes performed well, whereas 32 large-diameter corrugated metal pipes exhibited results that ranged from no damage to complete collapse. However, studies on the dynamic response of salt cavern gas storage facilities in an earthquake are rare.

In this paper a dynamic elastoplastic damage constitutive model is proposed to investigate the damage characteristics of rock salt during an earthquake. A numerical model of salt cavern gas storage facilities in China is established using the FLAC^{3D} software. The dynamic response and safety of a salt cavern gas storage facility are studied based on the proposed damage constitutive model and numerical simulations. Encouraging results were obtained, which can serve as technological references for the seismic design of salt cavern gas storage facilities.

2. Numerical model and parameters

2.1. Dynamic elastoplastic damage constitutive model

The damage constitutive model is the foundation for evaluating the safety of rock masses that surround salt cavern gas storage facilities during an earthquake. A dynamic elastoplastic damage constitutive model is proposed based on the Drucker–Prager criterion to determine the damage sustained by rock salt under seismic loads. Unlike the quasistatic excavation process of a cavern, under dynamic cyclic loads rock salt is characterized by greater hardening and fatigue damage. According to Guo et al. (2012), the Young's modulus and strength of rock salt increase with increased strain rate under dynamic loads and decrease with the fatigue damage under cyclic loads. The effects of dynamic load and cyclic load on rock salt properties are conflicting and are present concurrently. Therefore, both loads should be considered in the constitutive model. The Young's modulus of rock salt in the proposed dynamic elastoplastic damage constitutive model is written as

$$E_0 = P(\dot{\varepsilon})E \qquad (1)$$

where E_0 is the Young's modulus of rock salt considering damage, GPa; E is the Young's modulus of rock salt at the initial stress state, GPa; $P(\dot{\varepsilon})$ is the strain rate function and is obtained by experiments.