Journal of Natural Gas Science and Engineering 23 (2015) 281–293

Contents lists available at ScienceDirect

Journal of Natural Gas Science and Engineering

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

Safety evaluation of gas storage caverns located close to a tectonic fault

Tongtao Wang [a,*], Chunhe Yang [a], Hongling Ma [a], J.J.K. Daemen [b], Haiyao Wu [c]

[a] State Key Laboratory of Geomechanics and Geotechnical Engineering, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan 430071, Hubei, China
[b] Mackay School of Earth Sciences and Engineering, University of Nevada, Reno 89557, Nevada, USA
[c] Nanning Oil & Gas Transportation Sub-company, China National Petroleum Corporation Southwest Pipeline Company Limited, Nanning 530000, Guangxi, China

A R T I C L E I N F O

Article history:
Received 10 December 2014
Received in revised form
4 February 2015
Accepted 5 February 2015
Available online 14 February 2015

Keywords:
Gas storage
Salt cavern
Fault
3D geomechanical model
Safety evaluation

A B S T R A C T

Rock salt resources of China are distributed mainly in graben or half-graben basins, where many tectonic faults usually exist. Serious challenges are encountered for the safety of caverns close to a fault used for underground gas storage. Laboratory tests have been carried out to determine the mechanical and permeability parameters of Jintan rock salt samples obtained from the target formation where the caverns will be located. 3D numerical geomechanical models have been developed based on these parameters, Jintan salt mine formation characteristics, and the tectonic fault distribution. Effects of fault dip and distance between fault and an adjacent cavern on the safety of an adjacent cavern are discussed. The design parameters of a cavern close to a fault in Jintan salt mine are optimized. To verify the safety of a cavern with optimized dimensions, deformation, plastic zone, safety factor (SF), equivalent strain (ES), and seepage pressure are used as the assessment indexes. Results show that the cavern with optimized dimensions close to a fault can satisfy the safety requirement over the entire design life-time, and has a reasonable safety margin. The distance between the cavern and the adjacent vertical fault in Jintan salt mine should be no less than two times the maximum cavern diameter. The thickness of rock salt between cavern roof and bottom and horizontal fault should be no less than 40 m.

1. Introduction

Salt cavern UGS (Underground Gas Storage) is widely used to reduce the disadvantages of natural gas demand fluctuations and to cope with some other emergencies (e.g., overhauling, third-party damage, and geologic hazard) on pipeline grids (Yang et al., 2015a; Wang et al., 2013; Ahmet, 2012). Consumers' demand for gas changes daily and seasonally. During peak times, the largest amount of gas is needed (peak load), but a “base load” of gas is needed year-round. However, the supply from gas fields and the transport capacity of pipeline systems are basically constant. Fortunately, UGSs can balance the supply and demand to maintain a reliable gas supply system without interruptions or reductions. The target areas selected to construct salt caverns for UGS in southern China mainly include Jintan and Huaian salt mines in Jiangsu province, and Qianjiang and Yingcheng salt mines in Hubei province. The purpose of these caverns is to store natural gas, to help assure and stabilize the energy supplies of major industrial countries of the country. According to the geological prospecting results, these salt mines all are located in typical graben or half-graben basins, with the following characteristics: (i) rock salt in the middle of the basin has the largest thickness, and shows ring-shaped thinning or is partitioned by faults all around the edges; (ii) main faults exist at the boundaries, and a series of secondary faults have formed in the rock salt in the middle areas of the basin; (iii) faults have suffered different degrees of dislocation, and, generally, sink in the middle region and uplift at the edges; (iv) rock salt is primarily bedded salt, usually composed of many thin salt layers and interlayers (e.g. anhydrite, mudstone, and glauberite). Due to high permeability and porosity, and low strength, faults do not have the capability to store gas, and should be avoided in UGS construction. Therefore, UGSs are mainly built in the center areas of the salt basins during the early constructions in China in order to avoid the negative effects of faults. In order to assure the sustainable increase

* Corresponding author.
E-mail address: ttwang@whrsm.ac.cn (T. Wang).

http://dx.doi.org/10.1016/j.jngse.2015.02.005
1875-5100/

of China's natural gas consumption, the requirement of increasing the storage capacity and the scale of UGSs has become urgent, which makes that the negative effects of faults on the safety of the adjacent caverns are becoming inescapable. How to design and construct the caverns close to the faults becomes a critical problem in the Chinese engineering and academia because of the lack of a clear theoretical basis and design method for such facilities. Similar problems are also a difficult and hot issue in international engineering and academia. For example, the Solution Mining Research Institute collected tools for designing the safe distance of salt caverns to a domal boundary all over the world (Solution Mining Research Institute, 2013).

Fig. 1 presents a schematic diagram of caverns close to faults in a graben or half graben rock salt basin. The distance between faults and nearby caverns has significant influences on the cavern safety and allowable size. If the distance is too small, it may result in leakage and may affect the stability of the caverns; if the distance is too large, it leads to a waste of rock salt resources, and ultimately cause the decrease of cavern size and number and capacity of salt cavern UGS. As the safety assessment and design method of caverns close to a fault has not yet formed a unified viewpoint, cavern construction in areas close to faults is restricted in China. Field monitoring data show that the distance between caverns and faults (>200 m) used in the previous design is conservative. Therefore, studies on the safety and failure mechanism of caverns close to a fault are beneficial to increase the salt cavern UGSs size and applicability, and have a good application prospect in China.

The special characteristics (such as low strength, high permeability and porosity) of faults create many challenges for the safety of underground engineering. Many researchers have studied this problem. Lux et al. (2004) analyzed the mechanical response of a cavern close to the fault in the Epe salt mine by numerical simulations, and they proposed the allowable internal gas pressure. They pointed out that the effect of a vertical fault on the safety of an adjacent cavern was significant, and should be focused on in the design process. Lombardo and Rigano (2006) observed the dynamic response of a fault in Mt. Etna, Italy, during an earthquake, and found seismic intensity increasing greatly around the fault. Ardeshiri and Yazdani (2008) investigated the influence of faults on seismic behavior of underground caverns using numerical methods and pointed out the most critical situation of a single fault crossing the cavern section with the strike parallel to the cavern axis. Rafiqul Islam and Ryuichi Shinjo (2009) studied the interactions between a coal bed and a fault during mining and thought high deviatoric stresses in the rock masses around the fault were the key factor causing roadway collapse. Samuelson and Spiers (2012) investigated the changes of formation mechanical parameters during CO_2 injection in the lab, and thought the CO_2 injection did not cause the fault activation in the short time. Yan et al. (2012) discussed the effects of coal mining around a fault on the safety of a roadway, and found that coal mining could cause fault activation and the roadway damage. They proposed that there should be a safe distance between mining and fault. Sainoki and Mitri (2014) used dynamic numerical methods to simulate the influence of the friction angle, mining depth, position, stiffness and dilation angle on the fault activation during coal mining, and concluded that the friction angle of the fault was the most significant factor. In conclusion, a fault has a great influence on the safety of underground structures, and its action mechanism is complicated.

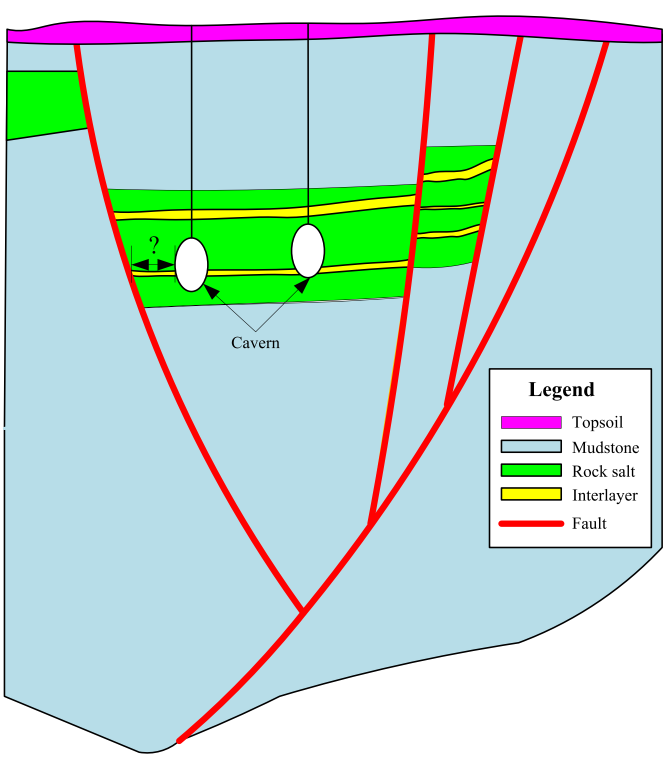

Fig. 1. Schematic diagram of caverns close to faults in a graben or half graben rock salt basin.

At the same time, a fault is also the key factor determining the sealing performance of a cavern close to a fault because of its high permeability and porosity, high internal gas pressure in caverns, and flammable and explosive character of gas. Many explosions of caverns serving as UGSs have taken place caused as a result of leakage to the surrounding environment, and many researchers have studied related problems. Bérest et al. (2001) discussed the main factors that affect cavern leakage, including fluid pressure distribution, geological environment, cementing workmanship and well architecture, and introduced two detection methods, viz., nitrogen and fuel-oil leak tests. Stormont and Daemen (1992) used the gas pressure pulse method to measure the permeability of rock salt less than 10^{-17} m^2, and their study showed that the permeability can increase more than 5 orders of magnitude over the initial (healed) state as the samples are deformed during deviatoric loading. Spangenberg et al. (1998) studied the influence of porosity on the transport properties of rock salt on a set of artificial porous rock salt samples. They showed that the influence of increasing confinement on the transport properties was much stronger than that of decreasing porosity for the mechanically compacted samples. Cosenza et al. (1999) carried out a field test in the Amelie Mine for the purpose of measuring rock salt permeability away from underground facilities by means of nitrogen and saturated brine injection. Their results confirmed that rock salt is permeable to gas and brine, even relatively far from underground openings. Moreover, they pointed out that the capillary pressure effect is significant and gas migration in salt is not controlled by Darcy's law after brine percolation. Schulze et al. (2001) discussed the permeability of rock salt when damaged, and confirmed that it is determined by the dilatancy damage boundary conditions. Hou (2003) studied the effects of drilling on the permeability of rock salt in the excavation disturbed zone (EDZ) by laboratory experiments. His results showed that the disturbance produced by drilling had a significant influence on the permeability of rock salt. Yuan et al. (2007) proposed a method to test the sealing and identify the leakage location of a cavern. Chen et al. (2009) built up an equivalent boundary gas seepage model to study the relation of gas seepage pressure and parameters of the contact face between salt and non-salt layers. Huang et al. (2011) assessed the sealing of a cavern in Qianjiang salt mine of China and thought it could satisfy the requirement of UGS