Journal of Natural Gas Science and Engineering 26 (2015) 61–71

Contents lists available at ScienceDirect

Journal of Natural Gas Science and Engineering

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

Gas seepage around bedded salt cavern gas storage

Tongtao Wang [a, *], Hongling Ma [a], Chunhe Yang [a], Xilin Shi [a], J.J.K. Daemen [b]

[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, NV, USA

A R T I C L E I N F O

Article history:
Received 7 February 2015
Received in revised form
27 May 2015
Accepted 28 May 2015
Available online 14 June 2015

Keywords:
Tightness
Gas seepage
Experimental analysis
Numerical simulation
Salt cavern gas storage

A B S T R A C T

Gas seepage serves as one of the indexes to evaluate the feasibility of salt cavern underground gas storage (UGS) in bedded salt formations because it has a significant effect on the tightness of the cavern. Tests have been carried out to obtain the permeabilities and porosities of the mudstone and interlayer cored from Jintan salt mine. Based on the experimental data and formation characteristics of the Jintan salt mine, a 3D geomechanical model of two adjacent caverns has been established to investigate the effects of operating time, interlayer permeability, pillar width, injection-production mode, and internal gas pressure on the gas seepage in the rock masses. The cavern dimensions and operating parameters are verified based on the numerical simulation results. Experimental results show that the porosity and permeability of the upper and lower formations of the rock salt layer range from about 1% to 20%, and from 1.0×10^{-16} m^2 to 6.6×10^{-16} m^2, and those of the interlayers range from 3.1% to 15.5%, and from 1.0×10^{-15} m^2 to 1.0×10^{-16} m^2 respectively. The porosity and permeability of interlayers at different locations show a great variability. This is mainly because of the presence of calcareous clay and brown mudstone in the interlayers, which show a notable characteristic of delamination and randomness. Numerical simulations indicate that the permeability of the interlayer has a greatly influence on the gas seepage pressure in the rock masses around the caverns, and it is also the key factor in the cavern sealing performance. The pillar between two adjacent caverns should satisfy both the requirements of mechanical stability and of gas seepage control. Asynchronous injection–production mode has great detrimental effect on the gas seepage pressure in pillars, particularly for narrow pillars. Synchronized injection–production is recommended for bedded rock salt cavern gas storages when pillars are narrow.

1. Introduction

Salt cavern underground gas storage (UGS) uses one of the best host rocks to store energy (such as oil, gas, and compressed air) and is widely used. Its construction will maintain a rapid growth for a long time (Yang et al., 2015a; Wang et al., 2013; Wang et al., 2015a; Yang et al., 2013; Ozarslan, 2012). China is one of the world's largest natural gas consumption markets. Its gas consumption has been growing faster and faster. Its gas consumption was 245×10^9 m^3 in 2000, 468×10^9 m^3 in 2005, 1075×10^9 m^3 in 2010, and will be about 2300×10^9 m^3 in 2015. Due to the consumption of gas showing typical seasonal and periodic variations, peak-shaving infrastructures become essential in the gas supply system (Yang et al., 2015a; Ozarslan, 2012). UGS is generally recognized as the most economic large scale gas storage infrastructure. The Yangtze River Delta region is the most developed region of China, and has strong demand for natural gas. It lacks depleted oil/gas reservoirs or aquifers but has abundant rock salt to construct the UGSs, such as Jintan salt mine, and Huai'an salt mine. Jintan salt mine is located in the center of the Yangtze River Delta region, and close to the artery pipeline of the West-East natural gas transmission of China. The rock salt of Jintan salt mine is mainly bedded rock salt composed of numerous thin rock salt layers and interlayers (e.g., anhydrite, mudstone, and glauberite) (Li et al., 2014). Based on previous research results (Yang et al., 2015a, 2009), the bedded rock salt of Jintan salt mine can satisfy the requirements for constructing UGSs. An UGS group is usually composed of many caverns. For example, the salt cavern gas storage group of Jintan salt mine consists of 63 caverns. During the UGS design, rock salt is usually assumed as impermeable. The permeability of the interlayers is relative larger, and can reach 10^4~10^6 times that of rock salt (Yang et al., 2009; Stormont, 1997; Yang and Andrew, 2010). This may lead to gas

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

http://dx.doi.org/10.1016/j.jngse.2015.05.031
1875-5100/

seepage between two adjacent caverns through the interlayers, especially when the two caverns run with asynchronous injection–production. Moreover, the alternating seepage pressure in the pillar may cause pillar failure. Therefore, gas seepage in the rock masses around the caverns is studied in this paper to provide reference information and data for the cavern design of Jintan salt mine.

Seepage gas has notable effects on the safety of salt cavern UGS. For example, a leak occurred through the corroded casing of a natural gas storage cavern in Barbers' Hill dome in 1980, Texas, and the natural gas likely moved through porous soil, which ultimately caused an explosion in a residence nearby Mont Belvieu (Thoms et al., 2000; Evans, 2009). Five years later, the leakage of natural gas caused another explosion and fire there again, which killed two people and prompted the evacuation of the entire town's population of more than 2000 residents. Therefore, sealing is one of the most important key indicators of natural gas storage cavern safety. Many studies have been made on the permeability of bedded salt and sealing evaluation of natural gas storage cavern according to the available literature. For example, Hou et al. (Hou, 2003) studied the effects of drilling on the permeability of rock salt in the excavation disturbed zone (EDZ) by laboratory experiments. The author found that the permeability of the EDZ was about 10^{-16} m^2 and decreased as the distance from the drilled hole increased. When the distance exceeded twice the hole diameter it equaled that of the original salt, about 10^{-21} m^2. The results show that the disturbance produced by drilling has a significant influence on the permeability of rock salt. Deng et al. (Deng et al., 2000) obtained the air permeability of gas reservoir caprocks by testing more than 500 core samples from different strata and geological ages. The permeabilities of the interlayers between rock salts ranged from 5.50×10^{-19} to 6.94×10^{-17} m^2. They were larger than that of rock salt by about 2–4 orders of magnitude under similar experimental conditions and exhibited anisotropy between the horizontal and vertical directions. Huang and Xiong (Huang and Xiong, 2011) used numerical simulations to study the tightness of salt caverns in Jintan salt mine of China, and demonstrated that the gas infiltration velocity along the damaged interface is much faster than along the salt rock and mudstone interlayer, and the damaged interface is the main gas leakage path. Chen et al. (Chen et al., 2009) built 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. The tightness of the West-1 and West-2 bedded salt cavern gas storages, located in Jiangsu province, China, was evaluated by the model. Wang et al. (Wang et al., 2015b) built up an equivalent permeability model to improve the sufficiency and reliability of using numerical simulation to assess the sealing evaluation of bedded salt cavern natural gas storage. The research results of the above scholars show that the mechanical and physical properties of non-salt beds in bedded rock salt have significant influences on salt cavern natural gas storage tightness.

The main motive for this paper is to verify the design parameters of caverns in Jintan salt mine that serve as underground gas storage from the viewpoint of the influence of gas seepage and to construct the gas seepage rules in the rock masses around caverns. Permeability tests have been carried out on samples of mudstones and interlayers between rock salts obtained from Jintan salt mine. A 3D geomechanical model of two adjacent caverns has been built using $FLAC^{3D}$ software based on the formation characteristic of Jintan salt mine. Effects of operating time, interlayer permeability, pillar width, injection-production mode, and internal gas pressure on the gas seepage of rock masses around cavern are investigated. Results provide basic data for the safety assessment of cavern leakage and cavern design parameter control in Jintan salt mine, and also can be used as reference for similar engineering works.

2. Experimental tests

2.1. Sample preparation

Two main interlayers cover almost the entire Jintan salt mine and will traverse the caverns. Moreover, secondary interlayers appear at some local areas. They may affect the gas seepage between adjacent caverns. Therefore, the interlayer samples are mainly cored from these layers. The permeabilities of the upper and lower mudstone layers of rock salt are much larger than that of rock salt, which may indicate a potential leakage risk. Mudstone located along the upper and lower edges of the rock salt is also cored. The permeability of pure rock salt of Jintan salt mine has been obtained in pervious study (Yang et al., 2009). Therefore, permeability tests of pure rock salt have not been carried out for this paper. Detailed information of core locations and petrographic description are given in the following.

(i) Mudstone cores obtained above cavern roof

Mudstone cores obtained from the cavern roof come from a depth ranging from about 862 to 873 m, and are composed mainly of grey calcareous mudstone. The upper parts of the cores are relatively intact, but the lower parts are crushed severely. Samples used in the tests are prepared mainly from the upper parts. The composition of the cores changes from mudstone to rock salt from the upper parts to the lower parts. Samples made from the upper cores contain more mudstone, and those made from the lower cores contain more rock salt with glauberite. The colors of these samples differ from each other as they contain different organic materials, which are mainly grey and black.

(ii) Interlayer cores obtained from cavern depth

The interlayers included in the cores are from a depth from about 960 m to 990 m, and their depths range from about 968 m to 971 m, 973 m–974 m, and 976 m–977 m. They are numbered as Ⅰ, Ⅱ, and Ⅲ respectively. The interlayers consist of the grey mudstone and brown mudstone, which alternate.

(iii) Mudstone cores obtained below cavern bottom

Mudstone cores obtained from below the cavern bottom come from a depth range from 1046 m to 1062 m, and are composed of the brown mudstone and celadon mudstone alternatingly. The cores containing argillaceous materials are charcoal grey. They are brownish red when the palm red mudstones are included.

Samples used in the tests are prepared roughly by sawing without water. Then, they are polished by hand to cater to the requirements of Code for Rock Tests of Hydroelectric and Water Conservancy Engineering (Ministry of Water Resources of the People's Republic of China (2007)). The diameter of the cylindrical samples is about 24–27 mm, and the ratio of sample height to diameter is about 2.0–2.5. The roughness of the end faces of the samples is less than 0.05 mm; measuring error of height and diameter is less than 0.3 mm; angles between two end faces and the axis of the sample deviate less than 0.25° from 90°. Fig. 1 shows the samples used in the tests. As numerous samples are used, the detailed dimensions of each sample are not included in this paper.

2.2. Experimental results and analysis

Considering that the mudstone will swell, and that the rock salt will dissolve, when they come in contact with water, the steady-state gas (nitrogen) method is used in the permeability tests.