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Investigation on the permeability characteristics of bedded salt rocks and the tightness of natural gas caverns in such formations

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A B S T R A C T

In China, the salt formations close to the lower reaches of the large natural gas routes and the main gas consuming regions are all bedded structures. The presences of non-halite or low-halite mudstone interlayers and interfaces (salt-interlayer) in these bedded salt formations increase the concern on the tightness of the natural gas caverns constructed in such formations. Therefore, different lithotypes of samples of bedded salt rocks have been prepared to determine their gas permeability evolution by steady-state and transient pulse-decay methods. The results show that the permeability of the samples is very low, within the range of 10^{-17} to 10^{-21} m^2 after well compacted. The permeability of the interface is comparatively the highest, steadily around the order of 10^{-17} m^2. A similar tendency of reducing permeability as deviatoric stress increases is found for all the samples; and unexpectedly there is no dilatancy and consequently steep increase of the permeability for all samples, even under very high differential stress. SEM (scanning electron microscopic) testing, as a supplement of tightness assessment, shows tight microstructure of all the bedded salt rocks cores. The experimental results indicate favourable performances for the tightness of natural gas caverns in such formations. Gas seepage around a gas cavern in such bedded salt formation was simulated by the $FLAC^{3D}$ software over a lifespan of 30 years. The results present that the interfaces act as the main channels for the gas to seep through. But the seepage distances in the vicinity of the cavern are so short that it causes a little influence on the tightness. Several factors, e.g., the internal gas pressure, the locations of interface, as well as the permeabilities of the interlayers were analyzed to investigate their effects on the tightness of a gas cavern. On the whole, the bedded salt rocks have enough low permeability and satisfactory tightness for the natural gas caverns constructed in.

1. Introduction

Natural gas consumption changes seasonally and periodically, so that the storage of gas plays a vital role to maintain the stability of the gas market (Jong, 2015). To ensure the sustainable supply of natural gas, more than 36 countries constructed their own gas storage facilities. In both the North-America (US + Canada) and Europe (OECD countries) the natural gas storage capacity measured by working volume is approximately 18% of the total annual consumption (International Energy Association, 2012). Due to the high safety margin (effectively avoiding accidents such as those due to lightning, war and terrorist attacks, etc.), lower cost and less occupation of land, underground storage facilities have much more extensive utilizations compared to the aboveground steel/concrete tanks (Li et al., 2012). With the rapid development of the economy, the total consumption of natural gas of China was 1800×10^8 m^3 in

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2014, and will rise to 2340 × 10^8 m^3 in 2020 (Wang et al., 2015a). However, up to now, the total amount of the natural gas stock is only 56 × 10^8 m^3 in China, as low as 3% of the annual consumption. Thus, for the China government, to construct more underground gas storage facilities has become an urgent duty to ensure the natural gas market.

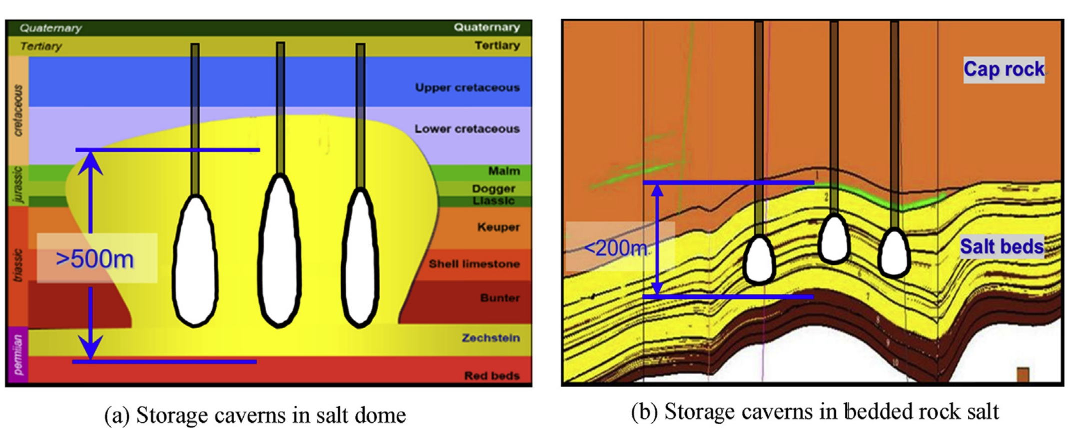
Three main geological formations are available for the underground natural gas storage, namely depleted oil/gas reservoirs, aquifers and salt caverns. The depleted oil/gas reservoirs generally exhibit the largest working volume but need a high proportion of cushion gas, and the withdrawal efficiency of them is low, as do aquifers. In addition, in East and Central China, where close to the middle and lower reaches of the large gas transmission routes (West-East Gas Transmission and Sichuan to East Gas Transmission) or close to the primary consumption markets (Yangtze River Delta region), there is a lack of depleted oil/gas reservoirs and aquifers but are abundant of large-scale salt formations in underground, which provides an alternative to build large-scale underground gas storage caverns in these salt beds (Zhang et al., 2014).

Rock salt is characterized by the low porosity and permeability, marked plasticity as well as capacity of self-healing when damaged. Thus, it is recognized as the best host rock to store crude oil and natural gas (Johnson and Seni, 2011; Yang et al., 2015). For instance, by the end of 2005, 198 × 10^8 m^3 natural gas was stored in salt caverns in Germany, 100 × 10^8 m^3 in France and 112 × 10^8 m^3 in Italy; In the USA, 23% of underground natural gas storage caverns were constructed in salt formations in 2011 and the proportion tends to increase continuously (Wang et al., 2015a). The China government plans to establish 5 huge natural gas storage sites in salt formations in central and eastern China by the end of 2020, the total storage volume of which will be as large as 4 × 10^7 m^3 (Yang et al., 2009).

Abroad, natural gas storage caverns are mainly constructed in marine deposit domal salt or thick salt formations (Staudtmeister and Rokahr, 1997; Hou, 2003). These types of salt beds have thick salt layers, homogeneity of components and low proportion of impurities. In such salt beds, the size of the caverns is often very large, usually 200–500 m in height, and up to 1,000,000 m^3 in volume (Fig. 1-a). However, the salt beds in China are typically thinly layered structures. These salt beds are characterized by complex tectonic structures, numerous interlayers and high impurity content (Li et al., 2012; Zhang et al., 2014; Yang et al., 2009, 2015), as visualized in Fig. 1-b. The higher proportion of impurities changes the composition and texture of the rock salt, but little is known about their effect on the permeability. The non-halite or low-halite interlayers often consist of anhydrite, argillaceous rocks, glauberite and shale, which usually have higher porosity and permeability as compared with rock salt (Zhou et al., 2009; Xiong et al., 2015). Their impacts on the tightness of the wall rock are also unknown. Moreover, bedded salt rock, as a typical composite material, stress concentration will form along the interface due to the unmatched deformations of the rock salt and interlayer near the interface (Li et al., 2014). Once the stress concentration exceeds the threshold shear strength of the interface, cracks will initiate and propagate, and hence induce slippage between the adjacent layers, and consequently results in percolation channels along the interface (Li et al., 2014; Muhammad et al., 2015). This will cause adverse effects on the tightness and stability of the storage caverns. Therefore, for the gas caverns in bedded salt rocks, the permeability of interlayer and interface as well as their influence on the tightness of the cavern are of utmost importance to be investigated.

For the permeability characteristics of relatively pure rock salt from domal salt, many studies from both the laboratory measurements and field surveys have been implemented (Hunsche, 1996; Alkan, 2009; Stormont, 1997; Consenza et al., 1999). Among all the studies, the damage criterion of the compression-dilatancy boundary (CDB) of the rock salt has been widely utilized for the cavern design and safety assessment (Hunsche, 1996). However, with regard to the permeability of the bedded salt rocks and the tightness of gas caverns in these strata, the studies seem too scarce to provide adequate guidance for engineering applications. Zhou et al. (2009) presented permeability tests on pure salt rock and anhydrite rock salt, they found that the rock salt has a permeability range between 10^{-16} m^2 and 10^{-18} m^2, but the anhydrite rock salt is almost impermeable. Xiong et al. (2015) revealed the gas seepage distance around a cavern in bedded salt rock but supplied no support of parameters from laboratory measurements. Adopting the steady-state method by using nitrogen as a permeant, Liu et al. (2015) conducted permeability measurements on mudstone cap rock and interlayers, taken from a pilot-well in Jintan Salt Mine, eastern China, which supplies some references for the tightness assessment of caverns in such salt formations. The interface that connects the adjacent rock salt and interlayer is a significant structure to greatly influence the tightness of a salt cavern. Although more attention is focussed on the permeability and evolution of the interface, due to the limitations of available cores, coring technique, and low-permeability testing technologies, the studies on the permeability of bedded salt rocks and its reaction to variable deviatoric stress, particularly the permeability characteristics of the interface, are still stagnant.

To solve the lack of knowledge about the permeability properties of the bedded salt rocks as well as the extreme lack of tightness



(a) Storage caverns in salt dome (b) Storage caverns in bedded rock salt

Fig. 1. Comparison of caverns, respectively located in a domal salt and in bedded salt rocks.