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Permeability characteristics of mudstone cap rock and interlayers in bedded salt formations and tightness assessment for underground gas storage caverns

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ABSTRACT

Permeability of nonsaline cap rock and interlayers is a key parameter for the assessment of the tightness of gas storage caverns in bedded salt formations. X-ray Diffraction, permeability tests, Scanning Electron Microscope studies and theoretical analyses have been performed for the mudstone cap rock and interlayers of a potential cavern in a bedded salt formation. The results show that the permeability of cap rock and interlayers is in the range of 10^{-18}–10^{-20} m^2, whereas the interface in between salt and interlayer behaves as if impervious. Applied confinement conditions significantly affect the permeability. The higher the applied hydrostatic pressure, the lower the permeability. Permeability decreases more than one order of magnitude with hydrostatic pressure increases, up to a certain “compression threshold pressure”. Permeability remains virtually constant, at an extremely low magnitude, once the hydrostatic pressure exceeds this “compression threshold pressure”. The intrinsic reasons for the low permeability have been revealed by SEM studies, and are as follows: (1) the grains making up the bulk of the mudstone are very small and extremely tightly cemented; secondary minute clay minerals completely fill the pores and fissures between grains of quarts and feldspar, etc., resulting in very little residual void space and reducing connectivity for fluid penetration; and (2) the boundaries between quartz, feldspar and other grains are mainly plate-shape cracks that are poorly interconnected while the finer matrix is very tight and crack-free. The mechanical compaction investigation shows that the plate-shape cracks are much easier to be compacted than sphere-shape pores, which contributes significantly to the decrease in permeability. A capillary tube model suggests that permeability decreases very rapidly in the initial stages of compaction, but decreases extremely slowly in subsequent stages. So the permeability obviously behaves differently before and after the “compression threshold pressure”. By comparison with previous studies, the research we launched demonstrates that the cap rock and interlayers are characterized by extremely low permeability in compression regions. Hence the requirements of tightness (except for the possible presence of Excavation Disturbed Zones) are basically guaranteed. Also, a recommendation is expressed as: to ensure higher tightness and safety, reasonable design and operating programs should be adopted to reduce the EDZs as much as possible.

1. Introduction

For decades, rock salt has been recognized as having low permeability (Stormont, 1990), high ductility, low creep resistance (Hunsche, 1994; Zhou et al., 2011, 2013) and self-healing capacity if damaged (Houben et al., 2013). For these reasons, rock salt is considered highly favorable and is widely used as a host rock for hydrocarbon storage and radioactive wastes disposal (e.g., Yang et al., 1999; Hunsche and Andreas, 1999).

The extremely low permeability of rock salt is a key prerequisite to guarantee the safety and tightness of the caverns. Generally, rock salt in undisturbed or well compacted state has extremely low permeability, usually less than 10^{-20} m^2 based on laboratory measurements (Peach, 1991; Stormont and Daemen, 1992). Numerous field experiments, such as those at the Waste Isolation Pilot Plant (WIPP) of the USA (Dale and Hurtado, 1996), Asse, in Germany (Hou, 2003), and Etrez, France (Berest et al., 2001) have resulted in values derived under in-situ conditions that show that the permeability is no more than 10^{-19}–10^{-20} m^2. Even under the condition of inhomogeneities in rock composition or interlayers existing in the large scale field, measured permeability is still less than ~10^{-18} m^2 (Peach, 1991; Stormont, 1997).

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However, the permeability of rock salt tends to increase fast if the texture of the matrix is disturbed or when high deviatoric stress occurs. So in the region of excavation disturbed zones (EDZs) induced by cavern excavation, such phenomena may appear (Alkan et al., 2007). And the permeability tends to approach gradually that of the intact rock salt beyond the EDZs. Researches (e.g., Cosenza et al., 1999; Li et al., 2007) indicate that the permeability is nearly immeasurable at a distance beyond 1× excavation radius. So for caverns leached in salt domes or thick bedded salt formations, the stability and tightness requirements can be satisfied by designing reasonable pillar widths, implementing safe running (operating) pressures, as well as injection and withdrawal practices, all of which are intended to ensure, at the least, that nearby EDZs do not mutually interact or overlap.

Gas and oil in storage is a strategic resource for dealing with complex international environments, as well as for coping with extreme natural disasters (Li et al., 2002). In China, the amount of strategic energy storage is far from the necessary amount, which has become a serious concern for the social stability. For instance, in recent winters, gas shortages have occurred in Beijing, Tianjin, Shanghai, Jiangsu, Zhejiang, and other places, seriously affecting the local regions' society and economy (Dong et al., 2010). To solve the gas shortage, the government spends dozens of billions of dollars every year importing LNG (Liquefied Natural Gas). Therefore, gas storage forms safety insurance that must be constructed, especially in regions of North China and regions along the Yangtze River. Gas storage also will be used in support of the Natural Gas Transmission Pipeline from West to East China, and the Sichuan-East Gas Transmission Pipeline.

Three alternative ways are used to store natural gas at depth, namely in depleted reservoirs, in deep saline aquifers (brine saturated porous formations), or in caverns in salt formations. In both regions of North China and regions along the Yangtze River, there are no available geological strata but salt formations suitable to construct storage caverns. Much different from the largely thick salt domes, the salt formations in China are thinly bedded highly heterogeneous formations, characterized by the presence of numerous halite layers, high content of impurities, and numerous insoluble nonsaline interbedded layers (glauberite, anhydrite, mudstone, shale, etc.). The petrophysical, hydrological, and mechanical characteristics of these thinly bedded heterogeneous rock salt formations are significantly distinct from those of salt domes and of relatively thickly bedded homogeneous salt formations (e.g., Liang et al., 2007; Li and Yang, 2006; Li et al., 2014). A sketch of a gas storage cavern in bedded salt formations is shown in Fig. 1. Although it is well known that rock salt has low permeability, data available for the fluid flow properties of nonsaline cap rocks and interlayers in bedded rock salt is insufficient for planning caverns in such strata. If the cap layers

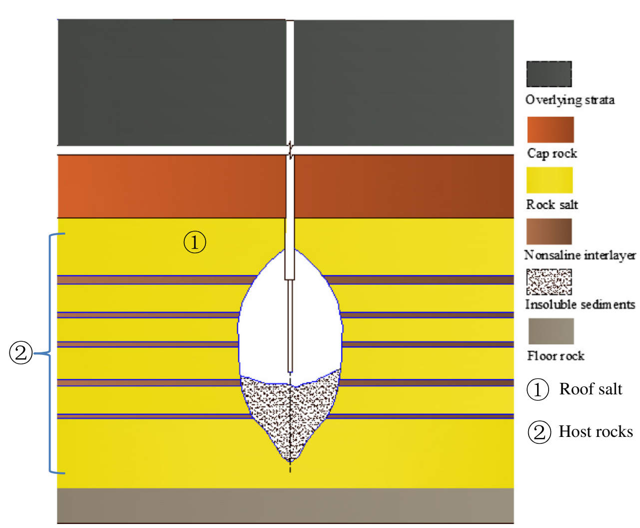

Fig. 1. Sketch of gas storage cavern excavated in bedded rock salt.

and interlayers have high permeability, the highly compressed natural gas may leak along the nonsaline layers, or along the interfaces, and then may require cavern abandonment. Moreover, once the gas flow connects with upper water-bearing strata, or nearby faults, geological disasters may occur, such as ground subsidence, surface collapse, explosions, land salinization (e.g., Bauer, 1999; Bérest and Brouard, 2003; Jing et al., 2011). Thus, research on the permeability of the cap rock and interlayers is extremely necessary and urgent.

In China, the cap rock and interlayers overlying and around caverns in bedded rock salt consist mainly of mudstone, shale, anhydrite mudstone, glauberite mudstone, and argillaceous siltstones (Li et al., 2006; Zhang et al., 2014). The Chinese criterion "The Assessment of Source–Reservoir–Cap rock" (Chen et al., 1999) points out that anhydrite, mudstone and shale often form an effective cap rock, while siltstone layers might be ineffective cap strata. Chen et al. (1999) also indicated that rocks with permeability of no more than 10^{-19} m^2 are effective cap rock. In our routine design work, this value is often adopted as the tightness criterion for gas caverns.

Geomechanical properties of rock vary greatly due to their different origins, mineralogical compositions, lithostratigraphic disposition, texture and diagenetic history, etc. Yang and Aplin (2010) state that the permeability of mudstone varies by up to 6 orders of magnitude with different clay minerals contents. Jobmann et al. (2010) show that the permeability of clay depends greatly on its damage degree and stress state. Chen et al. (1999) indicate that the higher the content of sand and gravel in the cap rock, the easier it is for fluid to break through; and the later the diagenetic state, the more brittle the rocks will be. Thus, it is not advisable to simply adopt the assessment of the performance of the cap rock of reservoirs or the experiences of salt domes for the safety assessment of caverns in bedded salt rock.

Research performed to date on highly heterogeneous bedded rock salt is relatively limited in scope. A general framework of theories for heterogeneous bedded rock salt also remains to be established. In particular, research on permeability properties of cap rock and interlayers remains far from sufficient. Therefore, it is necessary to carry out research on the permeability and its evolution of cap rock and interlayers, which will supply essential support for the assessment of tightness and safety of caverns in such formations.

This paper focuses on the tightness of cap rock and interlayers of a potential gas storage cavern. Porosity measurements, X-ray Diffraction studies, permeability tests, Scanning Electron Microscope (SEM) studies and preliminary theoretical analyses have been carried out. The permeability range of the samples has been determined. To develop a deeper understanding of the intrinsic mechanisms affecting “low permeability” and “compression threshold pressure”, SEM studies have been conducted. Connected with the compaction mechanism of the crack pattern in the rock, the mechanism leading to the “compression threshold pressure”, as well as the significant potential implications and applications has been revealed. Lastly, the permeability properties of mudstone are compared with those of salt rock and other lithotypes of cap rock, and a future project is proposed briefly. These studies provide significant new information for assessing the tightness of the gas caverns in thinly bedded salt formations, and supply further interpretation on the compaction of the mudstone at depth.

2. Permeability experiments

2.1. Sample source and sample preparation

The pilot well of the potential gas storages cluster is located in a bedded salt formation of Jintan, a city in between Jiangsu Province, Zhejiang Province and Shanghai City. According to the pilot well and geophysical data, the immediate cap rock, ranging from 770–880 m, is gray mudstone. The cored range of cap rock is 862.0–879.91 m. The preliminary design depth range of the cavern is about 880–1056 m, including the thickness of the roof salt. Two typical interlayers intersecting the