



Tightness and suitability evaluation of abandoned salt caverns served as hydrocarbon energies storage under adverse geological conditions (AGC)



Liu Wei^{a,b,c}, Chen Jie^{a,b,c,*}, Jiang Deyi^{a,b}, Shi Xilin^c, Li Yinping^{a,c}, J.J.K. Daemen^d, Yang Chunhe^{a,c}

^a State Key Laboratory of Coal Mine Disaster and Control, Chongqing University, Chongqing 400044, China

^b College of Resources and Environmental Sciences, Chongqing University, Chongqing 400044, China

^c State Key Laboratory of Rock and Soil Mechanics and Engineering, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan 430071, China

^d Mackay School of Earth Sciences and Engineering, University of Nevada, Reno, NV, USA

HIGHLIGHTS

- Tightness conditions are set to assess use of old caverns for hydrocarbons storage.
- Gas seepage and tightness around caverns are numerically simulated under AGC.
- κ of interlayers act as a key factor to affect the tightness and use of salt cavern.
- The threshold upper permeability of interlayers is proposed for storing oil and gas.
- Three types of real application are introduced by using the tightness conditions.

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ABSTRACT

In China, the storage of hydrocarbon energies is extremely insufficient partially due to the lack of storage space, but on the other side the existence of a large number of abandoned salt caverns poses a serious threat to safety and geological environments. Some of these caverns, defined as abandoned caverns under adverse geological conditions (AGC), are expected to store hydrocarbon energies (natural gas or crude oil) to reduce the risk of potential disasters and simultaneously support the national strategic energy reserve of China. Herein, a series of investigations primarily related to the tightness and suitability of the caverns under AGC is performed. Laboratory measurements to determine the physical and mechanical properties as well as porosity and permeability of bedded salt cores from a near target cavern are implemented to determine the petro-mechanical properties and basic parameters for further study. The results show that the mechanical properties of the bedded rock salts are satisfactory for the stability of caverns. The interface between the salt and interlayers exhibits mechanical properties that are between those of rock salt and interlayers and in particular is not a weak zone. The silty mudstone interlayers have relatively high porosity and permeability, likely due to their low content of clay minerals and the presence of halite-filled cracks. The conditions for evaluating the tightness and suitability of a cavern for storing hydrocarbons are proposed, including “No tensile stress,” “Factor of Safety” and “A threshold of leakage amount”. Three-dimensional numerical geomechanical models are developed to indicate how gas seepage evolves around the caverns. The results show that the permeability of the interlayers is a key factor in influencing gas seepage in the vicinity of the caverns and that interlayers form primary channels for gas migration. By evaluating the fluid seepage around the cavern by the above conditions, the upper-threshold permeability of the interlayers is suggested to be no more than 10^{-16} – 10^{-17} m² to guarantee tightness when storing natural gas and no more than 10^{-16} m² when storing oil. In principle, this work provides references for alternate uses of abandoned caverns for hydrocarbon storage under adverse geological conditions.

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1. Introduction

The consumption of energy, such as oil, natural gas and electric power, is characterized by noticeable periodically and seasonality [1], but the supply of energies is incapable to keep the consistency

* Corresponding author at: State Key Laboratory of Coal Mine Disaster and Control, Chongqing University, Chongqing 400044, China.

E-mail address: jiechen023@cqu.edu.cn (C. Jie).

with the use of energy all the time. Thus, large-scale energy storage facilities must be constructed along the energy transmission lines or close to the consumption regions so as to support the stability and reliability of the energy market [2,3]. Usually, energy will be stored when supply is surplus or during 'low loads'. Reliable energy storage system ensures that energy is available at any time of peak demand, and ensures a supply of energy in the event of a failure of the power transmission routes or encountering emergencies [4]. Pumped hydro storage [5,6], compressed air energy storage [7–9], thermal storage [10] and oil and gas storage [11–13] are the main methods to store energy.

Among all the types of energy storage, the China government pays most concerns and attentions on the storage system of crude oil and natural gas. All around the world, China has the 14th ranked of the oil and gas geologic reserves, but has the 2th ranked of the consumption amount of oil and gas. For instance, as of 2015, China consumed 5.43×10^8 tons of crude oil, in which the amount of import occupies approximate 60%, and consumed $1910 \times 10^8 \text{ m}^3$ of natural gas with an imported part of $624 \times 10^8 \text{ m}^3$ [14]. At present, China not only has an extremely high dependence of the imported hydrocarbon, but also has a poor system of the hydrocarbon storage, which furtherly increases the China government's concerns on its energy safety.

As is known, the members of the United Nations are recommended to own at least 90 days of the annual consumption as their strategic oil storage in civil. As that of China, the total oil storage amount is only 31 days at present; simultaneously, the natural gas storage should be of the international level of 15–18% of the annual use [2], but that of China is as low as 3%, far from enough to guarantee a reliable natural gas market. One main reason for these deficiencies is the lack of sufficient and available storage space. Moreover, the currently existing storage facilities of crude oil are mainly aboveground tanks located in coastal regions. Taking the first phase of the China's strategic petroleum reserve for example, the facilities are all concrete/steel tanks and located at four off-shore cities, those are Qingdao, Dalian, Zhenhai and Zhoushan, respectively [15]. These tanks are efficient to provide easy handling of the stored product, but their impact on the environment and on the safety of the neighboring inhabitants has given rise to serious protests and public distrust [16]. The government had to switch from the construction of surface tanks to much cheaper and safer underground storage facilities. As the main regions of energy consumption, central and eastern China lack depleted oil/gas reservoirs and aquifers, but have abundant bedded rock salt formations to allow the construction of large-scale underground hydrocarbon storage caverns, e.g., the Jintan Salt Mine, Huai'an salt mine and Yingyun salt mine [17]. These salt mines all are located close to the pipeline of the West-East natural gas transmission and Sichuan-East natural gas transmission of China [3,18]. To achieve the target of energy storage, up to 2020, the China government plans to build 5 large oil/natural gas storage sites are planned for construction in salt formations in the Central-Eastern Regions of China, with a total storable volume of up to $4 \times 10^7 \text{ m}^3$ [12,13].

Salt caverns alone can support large scale energy storage applications, and all around the world, they are regarded as the safest facilities to store natural gas, crude oil [19–21] and hydrogen [22,23], to store compressed air and even to permanently dispose of radioactive nuclear wastes [24,25] due to the impermeability and rheology of rock salt [26–28]. For instance, in Germany, $198 \times 10^8 \text{ m}^3$ of natural gas was stored in salt caverns by the end of 2005 [13]. In the USA, salt cavern gas storage represented 23% of the total natural gas underground storage in 2011 [29].

However, there are several inevitable disadvantages to build new salt caverns, such as: (i) long construction time: a single cavern with a volume approximately of $2.0 \times 10^5 \text{ m}^3$ usually takes 4–5 years to leach; (ii) high cost: a single cavern costs as much

as \$ 10–12 million to build; and (iii) strict requirements for technologies: in China, there is little experience in cavern construction, particularly in thinly bedded salts, so the construction tends to be more time-consuming and uneconomic. Nevertheless, the successful conversion of abandoned salt caverns to underground natural gas/oil storage would be a favorable solution for the prevention of geological disasters, for environmental protection, and for hydrocarbons storage.

Utilizing existing underground space, such as coal and salt mines where mining has been completed, to store gas/oil has a long history throughout the world. In Europe, hydrocarbon storage in abandoned salt caverns has been practiced since the early 1950s [30]. Examples include the Manosque facility in France and the Etzel salt dome near Wilhemshaven, Germany, which has been used since 1971 for crude oil storage. Starting in 1961, the Leyden mine was used to store natural gas for Colorado peak-day demands for almost 20 years [31]. Yang et al. [12,13] demonstrated the feasibility of storing natural gas in six abandoned salt caverns in Jintan, Jiangsu Province of China and carried out field surveys on the caverns' volume under operational conditions. The results show a satisfactory running state of the caverns. Evans and Chadwick [32] introduced the current situation and perspective of underground gas storage in the UK. They stated that, although hydrocarbons have been stored in abandoned mines, most of the facilities have been closed due to leakage. Therefore, prior to selecting caverns for storing hydrocarbons, it is necessary to evaluate the suitability of the caverns in which hydrocarbons are to be stored. The most important criterion is that gas/oil cannot leak from the cavern into aquifers and groundwater and thereafter to the surface [33], that is, the tightness of the cavern. However, because the critical conditions of the integrity of the host rocks are very strict, the conditions for converting abandoned salt caverns to underground hydrocarbon storage (UHS) are rare, even for the caverns in homogeneous salt domes.

As of the end of 2014, the total volume of all of the abandoned salt caverns in China has reached approximately $2 \times 10^8 \text{ m}^3$, and in the latest years, it has a rate of approximate $2 \times 10^7 \text{ m}^3$ per year to increase. After abandonment, the caverns are completely filled with saturated brine. The high-pressure brine exerts a certain restraint on the wall to sustain the cavern's stability, and the almost impermeable rock salt simultaneously prevents the brine from seeping into the surrounding strata. In this case, the cavern shrinks very slowly, and the brine pressure increases slightly until it balances with the geostatic stress [20]. Such a process typically takes place when the caverns are situated in salt domes or in thick salt deposits with a sufficient thickness and high grade of halite. However, the salt beds in central and eastern China are all complex bedded structure, usually consisting of numerous thin salt layers and non-halite interlayers [34–36], as shown in Fig. 1(a). The evolution of a cavern after abandonment is much different from that in a salt dome or in a thick homogeneous salt bed. So the conversion of them to UHS seems more challenging. Especially in some salt formations of China, e.g., Jintan Salt Mine, Huai'an Salt Mine [37], the interlayers are silt mudstone, silt sandstone and argillaceous sandstone, their permeability is as high as 10^{-15} m^2 or even higher. Brine easily penetrates into these permeable interlayers, leading to a series of negative consequences, such as rock matrix softens, pore pressure increases in wall rocks and internal pressure decreases in caverns. If the caverns are closely distributed with narrow pillars (Fig. 1(b)), the shrinkage of the cavern and the instability of the pillars and roof will be aggravated [38,39]. These adverse consequences may develop further and cause excessive subsurface subsidence and even collapse, posing serious threats to the safety of the aboveground infrastructures, such as residential buildings, factories and transportation facilities [38,40,41]. Moreover, brine is likely to flow upward along fracture zones or overlying faults

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