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Feasibility analysis of using abandoned salt caverns for large-scale underground energy storage in China

Chunhe Yang [a,*], Tongtao Wang [a], Yinping Li [a], Haijun Yang [b], Jianjun Li [b], Dan'an Qu [b], Baocai Xu [b], Yun Yang [c], J.J.K. Daemen [d]

[a] *State Key Laboratory of Geomechanics and Geotechnical Engineering, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan 430071, Hubei, China*
[b] *West-to-East Gas Pipeline Company Gas Storage Project Department, PetroChina Company Limited, Changzhou 213200, Jiangsu, China*
[c] *McDougall School of Petroleum Engineering, University of Tulsa, Tulsa, OK 74104, USA*
[d] *Mackay School of Earth Sciences and Engineering, University of Nevada, Reno, NV 89557, USA*

HIGHLIGHTS

- A method is proposed for the evaluation of using an abandoned salt cavern for energy (natural gas) storage.
- A feasibility analysis is given of China's first UGS (Underground Gas Storage) facility using an abandoned salt cavern.
- Numerical modeling has been used to investigate mechanical safety of a gas pressurized cavern.
- Chinese abandoned salt caverns show good feasibility of being converted to UGSs.
- China's bedded rock salt can meet the requirements for UGS.

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ABSTRACT

Rock salt in China is primarily bedded salt, usually composed of many thin salt layers and interlayers (e.g. anhydrite, mudstone, and glauberite). Thus, the feasibility analysis of abandoned salt caverns located in salt beds to be used as Underground Gas Storage (UGS) facilities is full of challenges. In this paper, we introduce the feasibility analysis of China's first salt cavern gas storage facility using an abandoned salt cavern. The cavern is located in Jintan city, Jiangsu province, China. The mechanical properties and permeability of the bedded salts are obtained by experiments. Based on the results of the analyses, it appears to be quite feasible to convert the abandoned salt caverns of Jintan city to UGS facilities. The stability of the cavern is evaluated by the 3D geomechanical numerical simulations, and the operating parameters are proposed accordingly. Results indicate that the maximum volume shrinkage of the cavern is less than 25% and the maximum deformations are less than 2% of the caverns' maximum diameters after operating for 20 years. It is recommended that the weighted average internal gas pressure be maintained as 11 MPa to control the extent of the plastic zones to a safe level. Safety factors decrease with operating time, especially those of the interface between rock salt and mudstone layers decrease significantly. Effective strain is generally greater than 2%, and locally is greater than 3% after operating 20 years. The maximum pressure drop rate should be kept to less than 0.55 MPa/day. Based on above proposed parameters, China's first salt cavern gas storage facilities were completed, and gas was first injected, in 2007. To check the status of the caverns after operating for 6 years, the volumes of the caverns were measured in 2013 by Sonar under working conditions. Measurement results show that the cavern shapes did not change much, and that volume shrinkages were less than 2%. Comprehensive results show that the feasibility analysis method proposed in this paper is reliable.

1. Introduction

Large-scale energy storage systems are used widely in the major industrial countries to reduce the disadvantages of energy demand fluctuations in electricity power grids [1–4]. Pumped hydropower, compressed air and natural gas energy storage are the main methods. The consumption demand for natural gas has similar fluctuations. 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

* Corresponding author.
E-mail address: chyang@whrsm.ac.cn (C. Yang).

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pipeline systems are basically constant. Therefore, the balancing of supply and demand is required in order to maintain a reliable gas supply system without interruptions or reductions. Large scale UGS systems can effectively overcome the disadvantages associated with the gas demand fluctuation, as well as some other emergencies. They can also greatly reduce the cost in long-distance gas transmission and can provide a steady gas source [5–10]. Because of these advantages, salt cavern UGS is widely used in many countries. About 554 salt cavern UGSs were in operation around the world by the end of 2012.

Salt caverns serving to store natural gas and compressed air, etc., has a long history [10]. As early as the Second World War, salt caverns were first used in Canada to store liquid and gaseous hydrocarbons. Britain used salt caverns to store crude oil during the Suez Crisis. Ten years later, Americans and Canadians began to use salt cavern for gas storage. Since then, salt cavern UGS had been widely used and developed. By the end of 2005, the number of salt cavern UGSs and working gas capacity were 15 and $100 \times 10^8\,m^3$ in France, 4 and $32 \times 10^8\,m^3$ in England, 41 and $198 \times 10^8\,m^3$ in Germany, and 8 and $112 \times 10^8\,m^3$ in Italy. Fig. 1 shows that the proportion of energy stored in salt caverns (mainly for natural gas) in the total reserved energy of America became bigger and bigger, and showed an accelerated trend in 1998–2008, according to information from the U.S. Energy Information Administration [11]. It increased from 11% in 1998, to 16% in 2005, and to 25% in 2008. Meanwhile, 31 salt caverns will be rebuilt and enlarged in the next few years to increase their reserves in the US [11]. By the end of 2012, there were 40 salt cavern gas storages in America. The British had invested 9.3 billion dollars to construct more than 20 UGSs in salt formations by 2010 and this would increase natural gas storage capacity by about 30% [12]. In conclusion, salt cavern storage has an important position in the international energy reserves, and will be constructed on a large scale in the future, for a long period of time.

With sustained and rapid development of its economy, China's external energy dependency increases. The net imports of petroleum products, including crude oil, oil, liquefied petroleum gas, etc., have reached 2.931×10^8 tons. The import of liquefied natural gas (LNG) and pipeline gas is $425 \times 10^8\,m^3$, accounting for about 28.9% of China's natural gas consumption in 2012 [13]. According to previous experience [14], the ratio of working gas volume in UGS to gas consumption should exceed 12% to assure the safety of the gas supply if the ratio of imported gas volume to gas consumption exceeds 30%. In China it was just 1.7% in 2012. It is much lower than the three main storage markets' 19% [14], and has caused many potential safety problems for China's gas supply, e.g., nationwide gas shortages causing many very negative impacts on China's economy and people's life in 2009. The Chinese government noticed the seriousness of the problem, and actively carried out research and construction of UGS. The Ministry of Science and Technology of China launched the National Basic Research Program of China "the Disaster Mechanism and Protection of Energy Reserves in Underground Storages ("973" Program)", which was mainly organized and implemented by the authors group. Research results have been used in the site selection and construction of salt cavern gas storages in Jintan and Huaian city in Jiangsu province, Qianjiang and Yingcheng city in Hubei province, and Pingdingshan city in Henan province, China. These engineering applications have demonstrated the research results with good practical implementation results [8,15–20]. Meanwhile, the China National Energy Administration formulated the "twelfth five-year" natural gas development plan in 2012, and invested 81.1 billion yuan to construct 24 UGSs to increase the ratio of working gas volume to gas consumption to 5% [21].

Salt caverns are one of the major UGSs in China. They have the following advantages compared with other types of gas storage [5,9–10]. (i) Flexibility. Salt cavern facilities operate under very high pressure, and can quickly inject or deliver large amounts of gas to the pipeline grid. As a result, these facilities are well-suited to meeting short-term changes in demand or supply. (ii) Cycling. Salt cavern operators can move natural gas in and out of these facilities more frequently, usually up to a maximum of 6–12 cycles per year, compared to traditional, seasonal gas storage where customers inject in the summer and withdraw in the winter. (iii) Requires less base natural gas. Salt cavern storage needs less base gas and has a higher proportion of working gas. (iv) Moderate distance to the consumer market. The rock salt mines of China are usually in the range of about 200 km to the consumers, which is an economical distance for the construction of UGS.

However, the disadvantages of the salt cavern construction are also very significant, as follows: (i) Construction time is long. (ii) Requires much more investment per cubic meter working gas than reservoirs in depleted oil and/or gas fields. (iii) Needs the supporting facility, e.g., brine treatment plant. For example, a cavern with a volume of $25 \times 10^4\,m^3$ will take four years to finish the construction, will require more than twenty million yuan, and will produce more than $180 \times 10^4\,m^3$ of brine. Therefore, converting caverns formed by brine production into gas storage has a good economic benefit. Jintan city of Jiangsu province, China, is a traditional brine production field, and has many caverns. By preliminary screening, 30 caverns with a total volume of $207.05 \times 10^4\,m^3$ are deemed suitable to convert to UGS. Although a single cavern has a small volume and an irregular shape, and a well with a poor cementing quality, etc., there are still lots of attractions to the engineers to convert these caverns into UGSs. Main advantages include: (i)

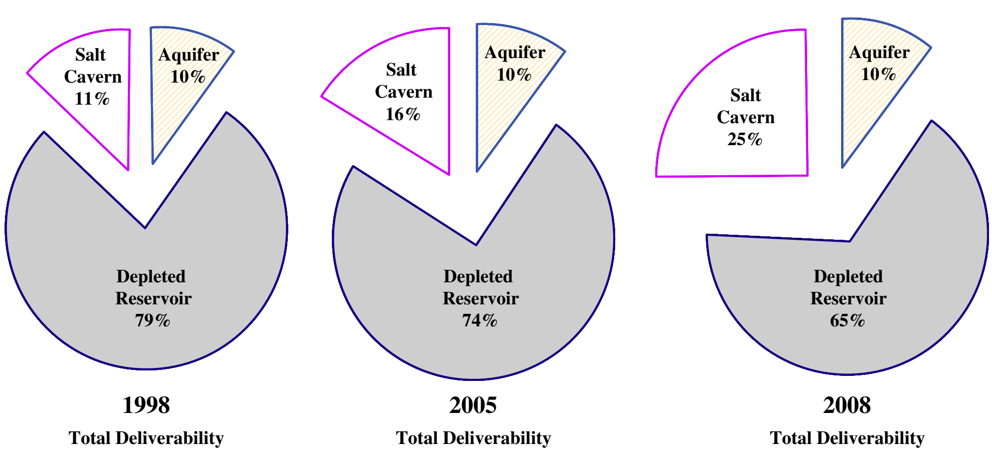

Fig. 1. Proportion of the natural gas stored in salt caverns as a fraction of the total USA stored gas [11].

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