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Salt cavern gas storage in an ultra-deep formation in Hubei, China

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ABSTRACT

The target formation of Jianghan salt district, Qianjiang city, Hubei province, China, for underground gas storage (UGS) construction has a depth of more than 1800 m. The cavern will be the deepest salt cavern UGS in Asia. A 3D geomechanical model of the proposed salt cavern UGS is built based on the geologic characteristics and mechanical parameters of the target formation. A new indexes system composed of displacement, volume shrinkage, plastic zone, dilatancy safety factor, and equivalent strain is proposed to quantitatively evaluate the safety of Jianghan salt cavern UGS. The thresholds of each indicator are proposed based on the characteristics of rock salt in China. By using the proposed indexes system, the cavern shape, dimensions, operating parameters and pillar width are optimized. Calculating results show that the optimized cavern has a slender cylindrical shape with a domed roof and an inverted cone bottom; its diameter ranges from 80 to 90 m, its height is about 210 m, and its free volume (accessible to gas) is about 50–65 $\times 10^4$ m^3. The maximum operating gas pressure is about 34 MPa, and the minimum gas pressure is no less than 17 MPa. The width of the pillar between adjacent caverns is about 2.5–3 times the cavern diameter. The gas storage capacity of a single cavern is about 1.1×10^9 m^3, and the working gas is about 0.7×10^9 m^3, which is about three times that of a single cavern in Jintan salt cavern UGS, Jiangsu province, China. The results indicate that Jianghan salt cavern UGS has a good feasibility for large-scale gas storage.

1. Introduction

Salt caverns serve as the best storage methods for oil, gas and hazardous waste. They have been widely used around the world. However, a salt cavern with a depth (at the casing shoe) of more than 1800 m is still rare. Based on available literature, there seem to be about four salt mine districts for brine production or gas storage with depths more than 1800 m. For example, Barradeel concession brine production field, Harlingen, the Netherlands, has a depth of more than 2500 m, and was closed in 2004[1,2]; Eminence salt cavern underground gas storage (UGS), Covington County, Mississippi, USA, has a depth of about 1800 m[3]; Aldbrough salt cavern UGS, East Yorkshire, UK, has a depth of about 1800 m[4]; and Atwick salt cavern UGS, East Yorkshire, UK, has a depth of about 1730 m.[5] Due to the rapid increase of natural gas consumption in China, more UGSs are urgently needed. Jianghan salt mine district located at Qianjiang city, Hubei province, is in the central zone of the middle reach of the Yangtze River. There are many large cities with millions of people around Jianghan salt mine, such as Wuhan, Yichang, Nanchang, and Changsha. The natural gas consumptions of these cities are increasing rapidly. To ensure the gas supply security, UGS construction has become urgent. The Chinese government decided to increase the UGS in Jianghan salt district. Compared with the other salt mines of China, the depth of the salt formation of Jianghan is much deeper, and exceeds 1800 m. There is a 7 m thick interlayer at the depth ranging 1979~1986 m, which separates the target formation used for the UGS construction into two individual parts with thicknesses of 120 m and 112 m respectively.

Fig. 1 presents a schematic diagram of the target salt formation and of the cavern shapes used for the construction of UGS of Jianghan salt district. The interlayers are numbered from top to bottom. The 12th interlayer is 7 m thick. Its bottom depth is 1986 m. This is the key interlayer determining the cavern shape and dimension. In the previous design it could not be confirmed whether controlled collapse of the 12th interlayer might take place. To decrease this risk, the target formation for UGS construction is selected as the formation between the 12th and 16th interlayers, viz., the target formation is 112 m thick. Considering that the target formation thickness is almost equal to that of Jintan, the cavern design is based on the cavern parameters of Jintan,

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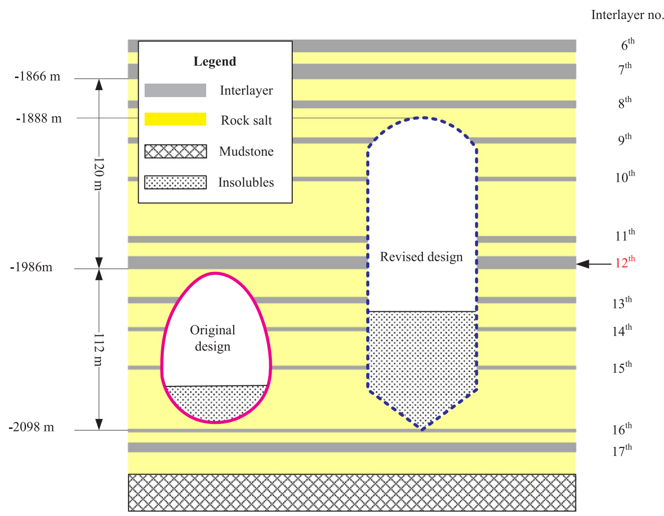

Fig. 1. Schematic diagram of the target salt formation and of the cavern shapes used for the construction of UGS of Jianghan salt district. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

viz., a pear-like shape with a volume of about 15×10^4 m^3.[6–8] The cavern construction was begun during January 2011. During the cavern leaching, the controlled collapse of the 12th interlayer successfully took place during December 2016 as a result of using some new technologies. Consequently the thickness of the target formation used for UGS construction increased from 112 m to 232 m, which creates three new difficulties for the construction of Jianghan salt cavern UGS. (1) Cavern shape and dimension design. Due to the increase of the target formation thickness, the cavern shape and dimension of Jintan UGS are no longer suitable for the Jianghan. Moreover, a cavern with larger dimensions improves the peak-load shaving capacity of UGS. Therefore, a new design of the cavern shape and dimensions should be carried out. As shown in Fig. 1, blue dash lines present the possible shape of the cavern in Jianghan UGS. We roughly calculate that in theory the volume of a single cavern will increase from the previous 15×10^4 m^3 to about 50×10^4 m^3. (2) Operating parameters optimization. Large depth means an increase of the difference between the maximum and minimum internal gas pressure to improve the peak-load shaving capacity. The maximum internal gas pressure is designed too low, which decreases the storage capacity of an UGS; if the internal pressure is too high, the cavern may fracture and lose its tightness. The stability of the cavern is directly positively related to the minimum pressure. A high minimum pressure is good for the cavern stability but not for the economic efficiency of the UGS operations. A new pressure range used in Jianghan UGS should be carefully optimized. (3) Allowable pillar width design. Compared with the salt cavern UGS at a small depth, the overlying pressures acting on the cavern of Jianghan are much larger. The displacements of the rock mass around the cavern will increase greatly. The pillar between adjacent caverns is the weakest part of the entire cavern system. How to determine the allowable pillar width becomes a critical issue, which determines the cavern safety and the scale of the entire UGS.

The overlying pressure to which the salt cavern UGS is subjected in ultra-deep formation seriously threatens the cavern safety, and many accidents have happened. For example, Eminence salt cavern gas storage, Covington County, Mississippi, USA, with a depth ranging from about 1740–2040 m, was constructed in a salt dome.[3,9] The overlying pressure of the target formation is about 39 MPa. The NaCI content of the formation is about 95%. Cavern-1, the first cavern of Eminence, was completed and started operations in 1970. A Sonar survey was carried out just after the completion of cavern leaching, which showed the cavern with a height of about 250 m and a maximum diameter of about 50 m. The internal gas pressure ranged from 6 to 28 MPa. In April 1972, the second Sonar survey was carried out. The results showed that the Cavern-1 volume had decreased by about 40%, and basically had lost its original design function. Cavern TE-02 of Tersanne salt cavern UGS in south-east France at a depth of about 1350–1550 m with an original volume of about 10×10^4 m^3, was completed in February 1970. After operating 35 years, it lost 60% of its volume.[10] The target formation for the UGS construction of Jianghan salt district has a depth ranging from about 1800–2100 m, which is basically equal to that of Eminence (1740–2040 m). This indicates that a similar development may take place at Jianghan salt cavern UGS, which is the study background of this paper.

Salt caverns for the storage of oil and gas have been widely used, and the critical problems related to the cavern construction, operation and abandonment are always hot issues focused on by researchers. Langer and Heusermann[11] indicated geomechanical analysis was one of the effective tools to evaluate the safety of a salt cavern used for hazardous waste disposal. They thought that how to precisely depict the mechanical response of rock salt and the loads to which the cavern is subjected were the critical issues. Heusermann et al.[12] investigated the long-term stability and usability of a salt cavern by using the LUBBY2 constitutive model predicting the creep characteristic of rock salt. Durup et al.[10] investigated the possible problems related to EZ58 and EZ53 caverns of Tersanne UGS after abandonment, and pointed out that the increase of the internal brine pressure was one of the challenges. Van Heekeren[1] studied the brine pressure in BAS-1 and BAS-2 caverns of the Barradeel concession brine production field, Harlingen, the Netherlands, after shut-up. They demonstrated that pressure build-up did not reach geostatic values (no fracturing) due to the combined effects of salt creep and salt (micro) permeability.

Li et al.[13] proposed a Cosserat-like constitutive model to predict the deformation and failure of bedded rock salt of China, and applied the model in numerical simulations. Lux[14] summarized the key issues for energy and waste storage in rock salt formations, and discussed the geomechanical characteristics and design safety criterions for salt cavern storage. He confirmed salt cavern UGS was an important element of current and future energy supply management. Bérest[15] analyzed the available accidents of salt cavern UGS and thought the cavern failure exhibited both brittle (roof fall, spalling, sluffing) and ductile (cavern closure) features. Wang et al.[16] proposed a safety assessment indexes system for salt cavern UGS based on the mechanical and formation characteristics of rock salt in China, and implemented the system for the safety evaluations of caverns close to old brine caverns and faults, cluster caverns, and old brine caverns converted to UGS.[6,7,17,18] Li et al.[19] simplified the salt cavern into a sphere or a cylinder to deduce analytical solutions of the ground subsidence above an UGS, and studied the effects of internal gas pressure on the ground subsidence.

Moghadam et al.[20] used an elasto-viscoplastic constitutive model describing dilatancy, short-term failure and long-term failure during creep of rock salt in a numerical model to study the effects of cavern dimensions and interlayers on the long-term cavern safety. Zhang et al.[21] deduced the subsidence of the ground above salt cavern UGS and discussed the effects of different factors on the subsidence. Shahmorad et al.[22] compared the responses of rock masses around salt caverns by using Burger, Power and WIPP constitutive models in the numerical simulation, and considered Power and WIPP models having advantages in predicting the mechanical characteristic of rock salt. Mahmoudi et al.[23] obtained the deformation and failure rules of rock salt under cyclic loads in the lab, and investigated thermo-mechanical problems related to the salt cavern UGS during gas injection and production. Mortazavi and Nasab[24] studied the long-term stability of salt cavern oil storage using numerical simulations, and indicated the cavern stability decreased with the increases of cavern depth and volume, and increased with the decrease of in-situ stress difference coefficient. From above literature review, we conclude: (1) Using salt caverns for oil and gas storage is still a research hot topic. (2) Geomechanical analysis coupled with proper constitutive model of rock salt and