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Safety evaluation of salt cavern gas storage close to an old cavern

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ABSTRACT

Uniaxial compression tests, triaxial compression tests, Brazilian disk splitting tests, direct shear tests and triaxial creep tests have been carried out on samples cored from Jintan mining district to determine their mechanical parameters. Based on the formation characteristic and the Sonar survey data of an old cavern, a 3D geomechanical model has been built of a cavern close to an old brine cavern. The effects of the distance between new and old caverns on the safety of the rock mass around the caverns are investigated. Deformation, plastic areas and volumes, effective strains, safety factors, and volume shrinkages are selected as the indexes to assess the safety of the caverns. The width of the pillar between the new and old caverns is optimized based on the calculated results. Experimental results show that the interlayer has large effects on the mechanical parameters of Jintan bedded rock salt, and should be considered in the numerical simulations. Numerical calculations indicate that the distance between the new and old caverns has large influences on the deformations, effective strains and safety factors, but has little effect on the plastic areas and volumes and volume shrinkages of the rock mass around the caverns. Although the dimensions of these old brine caverns are much smaller than those of the new ones, a distance between the new and old caverns of no less than two times the maximum diameter of the new cavern is proposed as the shape of the old cavern is poor.

1. Introduction

Salt cavern underground gas storages (UGSs) are being constructed in many areas of China. They are one type of the large scale infrastructures for natural gas storage and play an important role in ensuring the energy security of the country. The target areas for the construction of salt cavern UGS (such as Jintan, Huai'an, and Qianjiang salt mines) are also the traditional brine production areas. Many old brine caverns have been formed over the course of history. These old brine caverns usually are located in areas with a thick rock salt layer, which are also the preferred target zones for the new caverns used for UGS. As a result it becomes inevitable that the new caverns used as UGS are close to these old caverns. The shapes of the old caverns were not controlled purposefully because the aim of brine production is exclusively to improve the output. The horizontal dimensions of the brine caverns are usually large and cavern edges are highly irregular, which causes the cavern stability to be poor and to be affected easily by other factors (e.g., the construction of new cavern in the nearby areas). Moreover, the safety of these new caverns close to the old ones may be affected by the old caverns. For example, there are more than thirty old brine caverns in Jintan salt mine, which are distributed nearly around the whole UGS construction areas. Therefore, study on the safety of caverns close the old brine caverns is significant for improving the use efficiency of rock salt around old caverns and for optimizing the distance between the new and old caverns.

Many researchers have investigated related problems in the safety assessment and design parameter optimization of salt cavern gas storage, and much progress has been made. A brief introduction is given. Staudtmeister and Rokahr [1] summarized the design processes and parameters of salt cavern UGS systematically, and thought their proposed method satisfied the requirement of cavern long-term stability. They used numerical simulation to verify their results. Langer and Heusermann [2] thought the stability and integrity of salt cavern used as the host to dispose of hazardous wastes are very critical, and pointed out that modeling exactly the characteristics of surrounding rock mass (such as formation condition, in-situ stress and constitutive equations) is the key factor to predicting the stability of caverns. Swift and Reddish

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[3] built a numerical model of caverns located at the Winsford salt mine, Cheshire, England, used to store hazardous wastes, using FLAC software. The stability of the cavern was studied, and the numerical results were verified by the monitoring data of cavern roof deformations. Chen et al. [4] established a numerical model of abandoned brine production caverns converted to UGS of Jintan salt mine by Abaqus software, and studied the creep deformation and plastic damage zone. They proposed the acceptable internal gas pressure and the depth of the casing shoe. Bérest et al. [5] analyzed the massive roof collapse of caverns that occurred in 1873 at the Varangéville salt mine, Lorraine, France. They concluded that the floor cohesion and roof stiffness were the two most important mechanical parameters affecting the roof collapse. Wang et al. [6] investigated the effects of the deformation difference between the salt rock and the mudstone on the deformation and stability of salt cavern UGS. Wang et al. [7] introduced the cusp catastrophe model into the stability analysis of a pillar between salt caverns to improve the calculating accuracy of the stability safety factor by numerical simulations. Mohanty and Vandergrift [8] proposed a new method to analyze the long-term stability of caverns used to store dimethylmethane, and thought the internal gas pressure had notable effects on the cavern stability. Ji et al. [9] simulated the stability and volume shrinkage of salt cavern UGS group converted from old brine caverns, and found the relative locations of caverns in the group, depth difference, formation dip, cavern shapes and volumes could cause the differences in volume shrinkages and deformations between different caverns. Wang et al. [10] proposed a new model to design the shape and dimensions of salt cavern gas storage, and introduced the concepts of slope instability and pressure arch into the shape design of the lower and upper structures respectively. Yang et al. [11] analyzed the feasibility of China's first salt cavern gas storage facility using an abandoned salt cavern based on experiments, numerical simulations and field monitoring. They thought the abandoned salt caverns had a good feasibility of being converted into UGS and had great advantages, such as saving construction time and investment. Wang et al. [12] built a 3D geomechanical model of two adjacent new caverns to study the stresses, deformations and safety factors of the pillars. The allowable pillar width between two adjacent caverns of Jintan salt mine was proposed. From above review, we can conclude that (i) structural stability and tightness are the main factors that govern the design of salt cavern UGS; (ii) numerical simulation is an effective method in the safety assessment of salt cavern UGS.

The motivation for this paper is to determine the distance between the newly built cavern and the old brine cavern in Jintan salt mine to ensure the cavern safety and to improve the use efficiency of the rock salt around the old brine cavern. An old brine production cavern, which has been converted into UGS, is selected as the study target. Based on the Sonar survey data of the old cavern and the formation characteristics of Jintan salt mine, a 3D geomechanical model is built of the new cavern close to the old cavern. The effects are studied of the distance between the new and old caverns and operating time on the deformations, plastic areas, plastic volumes, effective strains (ES), safety factors (SF), and volume shrinkages of the new and old caverns. The distance between the new and old caverns is proposed based on the numerical results. The study provides the design parameters for a new cavern to be excavated near the old brine caverns in Jintan salt mine. This also can be considered as a case study for similar engineering in other areas.

2. Mechanical tests

To obtain the mechanical parameters of rock salt in the formation near the old cavern, cores have been extracted from the target formation. Uniaxial compression tests, triaxial compression tests, Brazil disk splitting tests, direct shear tests and triaxial creep tests are carried out on the samples prepared from the cores. The samples were prepared roughly by sawing. They were then polished by hand to meet the requirements of the test standard. [13] Due to the rock salt of Jintan being mainly bedded, pure rock salt, bedded rock salt, and mudstone samples have been prepared. Uniaxial compression tests, triaxial compression tests, Brazil disk splitting tests and direct shear tests are carried out on the RMT-150C rock mechanical test instrument. Triaxial creep tests are carried out on the XTR01 high temperature–pressure-creep testing system. The diameter of the cylindrical samples is about 100 mm, and the ratio of sample height to diameter is about 2.0–2.5 except for those used in the Brazil disk splitting tests. The diameter and height of the cylindrical samples for the Brazilian disk splitting tests are about 100 mm and 50 mm respectively. The roughness of the end faces of the samples is less than 0.05 mm; measuring error of height and diameter is less than 0.3 mm; angles between two end faces and the axis of the sample deviate less than 0.25° from 90° .

2.1. Uniaxial compression tests

To obtain the uniaxial compression strength, Young's modulus and Poisson's ratio, uniaxial compression tests are carried out on the pure rock salt, bedded rock salt, and mudstone samples. Fig. 1 shows photos of rock salt, bedded rock salt and mudstone samples after uniaxial compression tests. In Fig. 1a a main fracture runs through the entire rock salt sample, which indicates a splitting failure. The rock salt sample keeps a good structure, and the particles remain compact and dense. This is because when the loads reach a limit, the fracture is formed and the compressive stresses decrease suddenly. However, the sample heals subsequently. Moreover, the load capacity of the fractured sample recovers to the original level under the compressive stresses. Therefore, there are no obvious fractures in the salt crystals of the sample. Poisson effect is shown notably in the failure of the bedded rock salt (Fig. 1b). Transverse and longitudinal damages both exist. Crystal particles show a loose connecting state, and there are apparent tensile fractures between these crystal particles. This is because there are many interlayers in the bedded rock salt, which have a higher strength than the rock salt. Moreover, the thicknesses of the salt between two adjacent interlayers are small. When the uniaxial loads reach a limit, the rock salt between the two adjacent interlayers fails first. This causes the uneven deformations and then the failures of the interlayers. As shown in Fig. 1c, there are many main fractures in the mudstone sample after the uniaxial compression tests, and some of the fractures change their propagation directions. This is because the mudstone is brittle and contains many weak joint planes, which makes that the splitting failures along these joint planes are induced easily under the external loads.

Table 1 lists the uniaxial compression test results of rock salt, bedded rock salt and mudstone samples. The average uniaxial compression strength of the mudstone samples is the largest and that of the rock salt and bedded rock salt samples are basically equal. The reason for this is that the mudstone samples contain lots of $CaSO_4$ and some other small salt crystals, which are connected intimately with the argillaceous components. This improves the uniaxial compression strength of the mudstone.

2.2. Triaxial compression tests

To obtain the cohesion and internal friction angle, triaxial compression tests are carried on five rock salt samples, four bedded rock salt samples and three mudstone samples. Considering