International Journal of Rock Mechanics & Mining Sciences 94 (2017) 43–54

Contents lists available at ScienceDirect

International Journal of
Rock Mechanics & Mining Sciences

journal homepage: www.elsevier.com/locate/ijrmms

Physical model test and numerical simulation for the stability analysis of deep gas storage cavern group located in bedded rock salt formation

Q.Y. Zhang[a], K. Duan[b,*], Y.Y. Jiao[c], W. Xiang[a]

[a] Research Center of Geotechnical and Structural Engineering, Shandong University, Jinan, China
[b] Department of Civil Engineering, The University of Hong Kong, Hong Kong
[c] Faculty of Engineering, China University of Geosciences, Wuhan, China

ARTICLE INFO

Keywords:
Geo-mechanical model test
Gas storage
Rock salt
Stability analyses
FBG sensor

ABSTRACT

The stability of gas storage cavern complex constructed in bedded salt rock formation might be influenced by multiple factors during the operation process. In order to assess these effects, three-dimensional rheological model tests were conducted in this study. Physical model with four ellipsoid caverns were constructed with scaled in-situ stresses applied through independent sets of hydraulic jacks and internal pressure applied by digital-controlled latex balloons. Influences of different factors on the deformation properties of surrounding rock were systematically evaluated, including the gas recovery and injection rate, the loss of pressure, the extremely low and high gas pressure, and the pillar width and pressure difference between adjacent caverns. Test results revealed that the deformation of the cavern wall was accelerated when the gas extraction/injection rate exceeds 0.65 MPa/d. Loss of internal pressure dramatically promoted the deformation. Tertiary creep stage arose when the internal pressure was too low (3 MPa) or too high (22 MPa). Internal pressure difference and pillar width worked together to affect the deformation properties. Tests results obtained in this study provided physical evidence for the safety analysis of cavern group as well as the optimization of design and operation scheme. These results can also serve as benchmark for the validation of numerical models.

1. Introduction

Underground storage is the most efficient and secure manner to store hydrocarbon energy sources, such as natural gas and petroleum.[1] Rock salt has been commonly accepted as an ideal medium for energy reserves because of its low permeability and self-healing capacity.[2–4] Rock salt caverns can be located in a salt dome or in a bedded deposit.[5] For the latter case, comprehensive understanding of the deformation properties of the gas storage caverns under different operation conditions is essential for the global stability evaluation, the failure analyses, and the optimization of caverns arrangement and mode of operation when intensive underground gas storage caverns are constructed.[6]

In the laboratory, extensive experimental studies have been conducted in order to understand the fundamental mechanical properties of rock salt under different stress conditions.[7–9] Tests have been conducted on the rock salt,[3] the bedded rock salt,[10] the interlayers, and the interface between the rock salt and beddings. Experimental results show that the interlayer has significant effects on the mechanical behaviors of bedded rock salt and have been considered in the numerical simulations.[10,11] The mechanical test results provide the basic parameters for the numerical simulations. A series of constitutive models have been proposed to characterize the responses of rock salt under different stress conditions based on the experimental data.[12–14]

Numerical methods, e.g., the finite element or the finite difference methods, have been adopted to analyze the stability of gas storage cavern,[6,10,15] to optimize the allowable pillar width,[5] and to evaluate the safety of new cavern close to old cavern.[16] Normally, numerical models were generated taking into account the geological situation, loading conditions, geometric layout and material parameters. However, the existence of deposit layers raises the risk of gas leakage and caverns may interact with one another. As the physical settings of underground caverns become increasingly more complex, the complexity and uncertainty of the geological, geometrical and geo-mechanical properties of different materials induce a great challenge to the numerical model.[17–19] Unlike other underground excavation projects (e.g., tunneling, drilling and underground hydropower stations), the gas storage caverns are normally formed by solution and thus are hidden and deeply buried.[16] Field monitoring is difficult to be carried out and in-situ information about the deformation and stability of storage caverns is limited, which inevitably becomes a main constraint

---

* Corresponding author.
E-mail address: kangduan22@gmail.com (K. Duan).

http://dx.doi.org/10.1016/j.ijrmms.2017.02.015
Received 30 July 2016; Received in revised form 16 January 2017; Accepted 28 February 2017

on the verification of numerical models. To this end, physical model tests at reduced-scale provide a promising avenue.

Well-designed experiments may yield important insights into behaviors which are not available from numerical simulations.[20] Geo-mechanical model test is one of the most important means of physical model test to investigate the stability of large-scale geotechnical engineering structures. Once the similarity principles are satisfied, the geo-mechanical model test is expected to characterize the prototype quantitatively. Geo-mechanical model tests have been successfully applied in the stability assessment and failure analyses of tunnels,[21–23] underground excavations,[20,24–26] high arms arch dams,[27–29] and mining-related projects.[30–32]

In this study, multi-cavern model is constructed taking the Jintan gas storage cavern as prototype to investigate the stability of underground cavern group during the operation process, with particular focus on evaluating the influence of various risk factors which might be encountered. These factors include the gas injection and extraction rate, the loss of internal pressure, the extremely low/high internal pressures, and the pillar width and pressure difference between adjacent caverns.

2. Background of the Jintan gas storage project

The Jintan gas storage project is selected as the prototype in the current study as it has been extensively investigated both experimentally and numerically for the past decade and abundant data is available. There are about thirty abandoned brine production caverns in Jintan salt mine, which locate in Jiangsu Province, China. Some of them have been successfully converted into underground gas storages. These caverns are the first gas storage facilities utilized in China.[2] Fig. 1(a) illustrates the schematic diagram of the typical geological profile of the Jintan gas storage caverns.[2] According to previous Sonar survey results, the shape of the cavern is approximately ellipsoidal cavity. The depth of the caverns is 1011.8 m with an overlay of rock salt (31.85 m) above the dome. There are two main interlayers cross the upper and lower section of the cavern with the thickness of 2.5 m and 3.0 m and their main components are mudstones. The physical and mechanical properties of the rock salt, the mudstone and the interlayers are provided in Table 1.[33,34]

The spatial range of the test prototype is determined as 400 m×400 m×400 m as shown in Fig. 1(b). The caverns are idealized to be ellipsoid-shaped with a semi-major axis of 70 m and a semi-minor axis of 30 m. In this study, four storage caverns are modeled which lie on the same horizontal plane and present rectangular distribution. The distance between adjacent caverns, which is also known as the pillar width (W), is set to be $1.5D$ and $2.0D$ (D represents the minor axis of the ellipsoid), respectively.

3. Setup of the geo-mechanical model

3.1. Similarity principles

In order to conduct the geo-mechanical model test, the physical model must satisfy a series of similarity principles which means that the physical features of the model should be similar to those of the prototype in terms of geometry, physical and mechanical properties, boundary conditions and initial states.[28] According to the theory and dimensional analysis, these similarity requirements can be deduced from force-equilibrium equations, geometry, Hooke's law, and boundary conditions.[24,27,35] From the theory, some similarity coefficients (C_i), defined as the ratios between properties of prototype and model, must be constant:

$$C_i = \frac{i_p}{i_m} \tag{1}$$

where i_p and i_m denote the corresponding parameter of the prototype and the physical model, respectively. These properties can be the weight by volume (γ), geometry (L), time (t), Young's modulus (E), Poisson's ratio (μ), coefficient of friction (f), stress (σ), strain (ε), shear strength (τ), and displacement (δ). Also, the following similarity principles should be satisfied in the physical modeling [20,27]:

$$C_\sigma = C_\gamma C_L \tag{2}$$

$$C_t = \sqrt{C_L} \tag{3}$$

$$C_\sigma = C_\tau = C_C = C_\delta = C_E \tag{4}$$

$$C_\mu = C_\varepsilon = C_{\mathrm{f}} = 1 \tag{5}$$

In the test, the geometry ratio (C_L) is held as constant. Once the similarity coefficient of density (C_γ) is determined, the other ratios could be readily obtained by solving Eqs. (2)–(5).

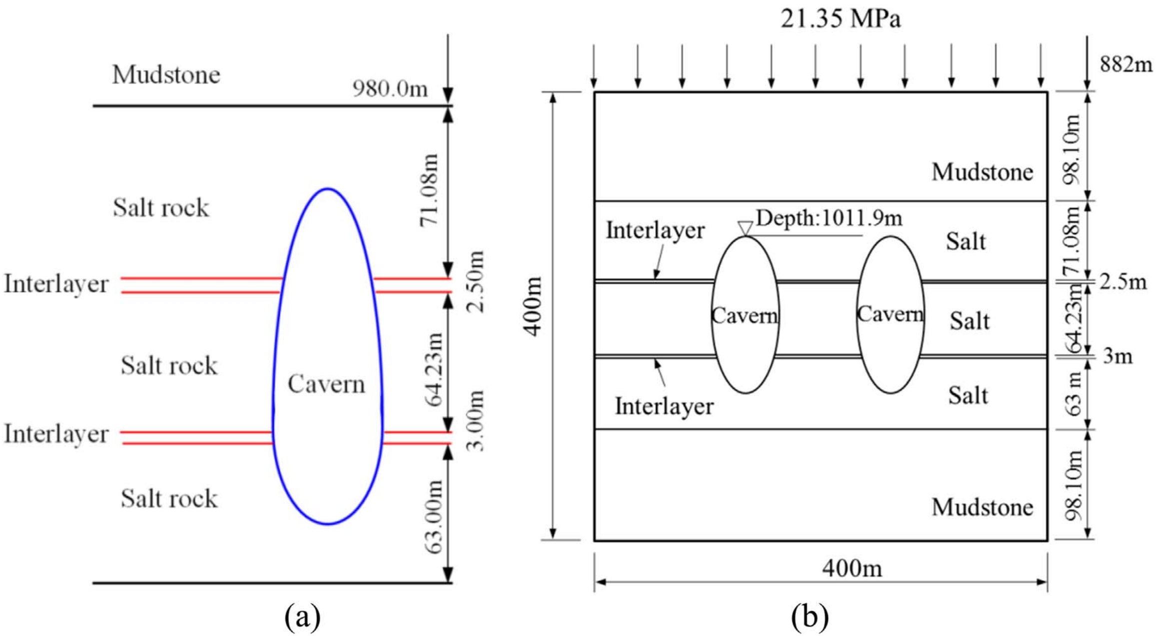

Fig. 1. (a) Schematic diagram of the typical geological profile of Jintan gas storage caverns [2]. (b) Range of the prototype modeled by the physical test in this study.