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Physical model test of Jintan underground gas storage cavern group

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Abstract. In the present study, a physical model was built for the Jintan underground gas storage cavern group according to the similarity theory. In this regard, four ellipsoid caverns were built with scaled in-situ stresses and internal pressure. Then the stability of underground caverns was analyzed. The obtained results demonstrate that loss of internal pressure adversely affects the safety of caverns and attention should be paid during the operation of gas storage.

Keywords: gas storage; physical model test; rock salt cavern

1. Introduction

As part of China's ambitious "West-to-East natural gas transmission project", it is necessary to use salt caverns as underground gas storage. The salt cavern in Jintan District is the first underground gas storage plant in China. It should be indicated that the idea of establishing underground gas storage caverns in rock salt has several challenges, including cavern stability, tightness of layers, evacuation and reuse, and designing appropriate operating parameters (Taheri and Pak 2020, Parkes *et al.* 2018, Mu *et al.* 2021). To overcome these challenges and ensure the safety of caverns, it is necessary to study geological tectonics, rock mechanics and creep damage characteristics, and gas storage tightness of the salt caverns and perform a comprehensive risk assessment.

Considering recent developments in the construction of salt caverns for underground gas storage, it is of significant importance to analyze the stability and failure of such cavern group. The present study is focused on the stability analysis of salt rock gas storage caverns in the Jintan District. It is intended to establish a physical model and study the problem. This article is expected to provide a guideline for the construction and operation of the Jintan underground gas storage cavern group.

2. Model test method

2.1 Geo-conditions

Jintan salt cavern is a 60 km^2 underground salt mine located in Jintan city, Jiangsu province, China. The total reserves of this massive salt mine are estimated at more than 16 billion tons. With the start of the "West-to-East natural gas transmission project" and increasing demand for fossil fuels in China, the Jintan salt mine has been considered as an important underground oil and gas storage project in the Yangtze River Delta area. Based on the results of the cavity dissolution and pressure test, these salt caverns are capable of storing 999 m^3 of gas (Zhang *et al.* 2017, Yin *et al.* 2020).

This paper is intended to study the stability of underground cavern groups during operation. Fig. 1 shows the geological profile of the studied area, indicating that there are four ellipsoid storage caverns. The cavern depth and the overlay of rock salt above the dome are 1011.8 m and 31.85 m, respectively. Moreover, it is observed that two mudstone interlayers cross the upper and lower section of the cavern.

2.2 Similarity principles

Studies show that the similarity principle between the established model and the real problem is an affecting parameter in the physical model test (Hao *et al.* 2018, Roberts *et al.* 2015, Nam *et al.* 2020). Based on the performed analyses, the established model satisfies the similarity conditions of the Jintan salt cavern from different aspects, including geometric parameters, physical and mechanical properties of the rock mass, and the applied load.

2.3 Setup of the physical model

The test prototype were 600 m long, 600 m wide, and 560 m high. The major and minor axes of ellipsoid caverns were 84 m and 36 m, respectively. It was assumed that all four caverns were 1000 m deep and at the same depth. The distance between the center points of the four caverns was 72 m, which was twice the cavern diameter. Considering a 56 m high sediment region above the cavern bottom vertex, the cavern was 112 m high. The mudstone interlayer was 2 m thick at a height of 24 m above the horizontal plane of the ellipsoid center point. Moreover, the dead weight of the remaining 778 m was calculated by applying the pressure using a jacking device.

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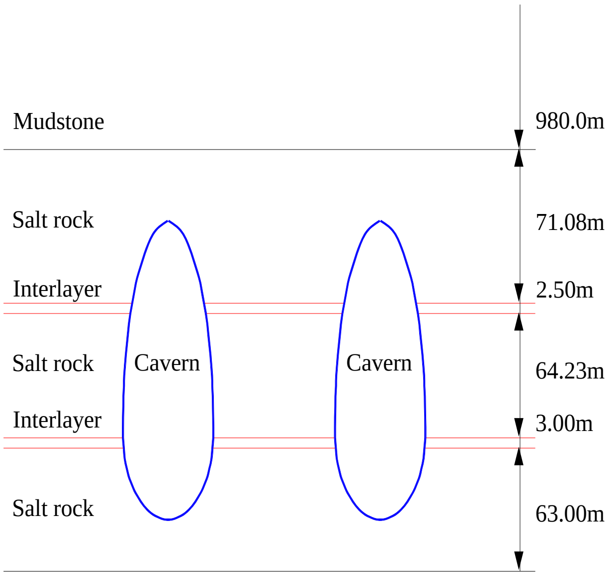


Fig. 1 Geological map of Jintan cavern


Fig. 2 Photo of the test system

The loading apparatus for the model test is shown in Fig. 2. The length, width, and height of the model were 750 mm × 750 mm × 700 mm, respectively, indicating that the model scale was 1:800. To construct the model, powder materials were compressed into small bricks, which were components of the model. It was worth noting that equivalent materials were used to simulate the mudstone, rock salt, and interlayers. In this regard, barite powder, bentonite, and glue were used.

Rock salt and mudstone samples had been retrieved from the site, and cored specimens were tested for their properties in the laboratory. Table 1 shows the mechanical parameters of the rocks as well as the expected properties of their similar materials, which were calculated based on the similarity ratios.

The prepared four ellipsoid molds had a diameter of 90 mm and were installed in the designed position (Wang *et al.* 2015, Yang *et al.* 2016, Zhang *et al.* 2017). Fig. 3 shows that latex balloons were then installed on the prepared caverns. During the experiment, the operation of gas injection and recovery was

Table 1 Mechanical properties of materials

Parameters	Prototype		Model	
	Rock salt	Mudstone	Rock salt	Mudstone
Young's modulus (GPa)	18	4	0.0225	0.005
Poisson's ratio	0.3	0.3	0.3	0.3
Cohesion (kPa)	1	0.5	0.00125	0.000625
Friction angle (°)	30	30	30	30
Density (kg/m^3)	2150	2800	2150	2800

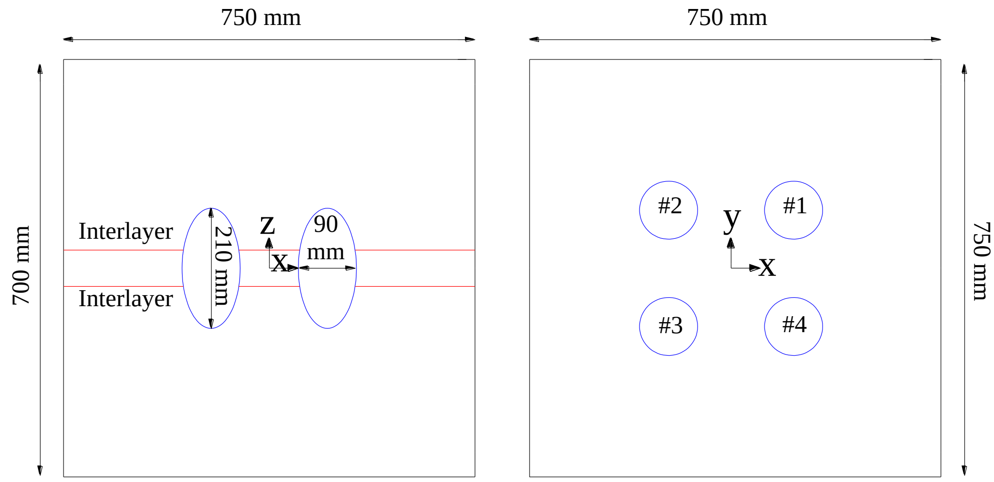

Fig. 3 Latex balloon

simulated by injection and extraction of air from the balloons using the servo-controlled system. During the model construction, the transducers were installed at the designed positions. Fig. 4 illustrates the longitudinal and transversal profiles of the physical model. Except for the free top surface, all surfaces were normally constrained.

The test device consisted of a loading unit and a data logger. During the experiment, the gravity of the overlying layer and internal pressure were applied. The former one was provided by the loading unit and an oil pump, while the internal pressure was provided using a gas pump. The normal pressure of 30 kPa was applied to the top surface, while the other five surfaces were subjected to normal constraints. The data of displacement and strain measured by the displacement transducers and strain gauges were recorded by the data logger. Studies show that the deformation of the surrounding rock is the main cause of failure in the gas storage caverns. Fig. 5 illustrates the schematic layout of measuring points at levels of -18 mm and 33 mm. The displacements in x-direction at points 1 and 3, and in y-direction at points 2, 4, 5, and 7 were monitored.

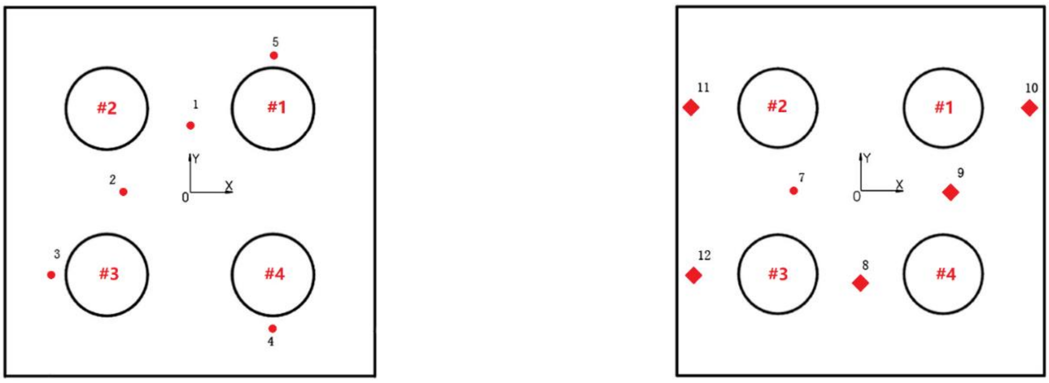
2.4 Loading scheme

During the experiment, the internal pressure of four caverns was increased from 0 to 22 MPa. Then the internal pressure of cavern #2 was reduced from 22 to 0 MPa, while the other three caverns kept the pressure of 22 MPa. The horizontal and vertical displacements and strains are measured. The balloons remain in place during the pressurization.



(a) longitudinal profile (b) transversal profile

Fig. 4 The longitudinal and transversal profiles of the physical model



(a) Level -18 mm (b) Level 33 mm

Fig. 5 Measuring points for displacement

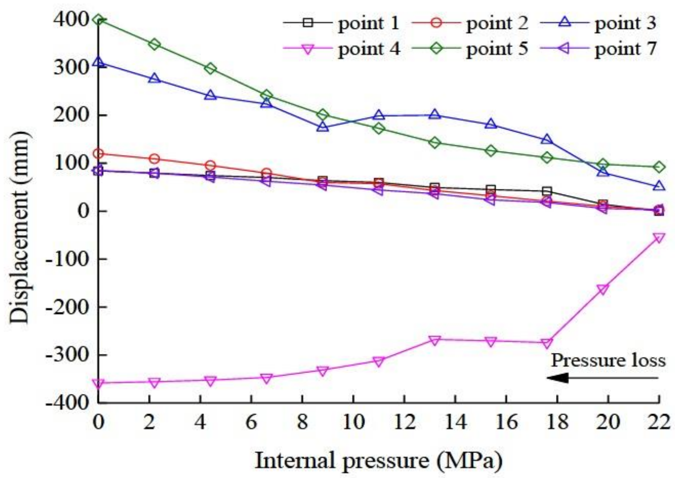
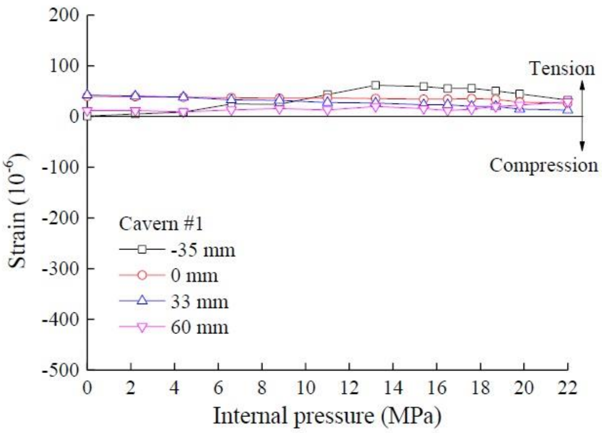


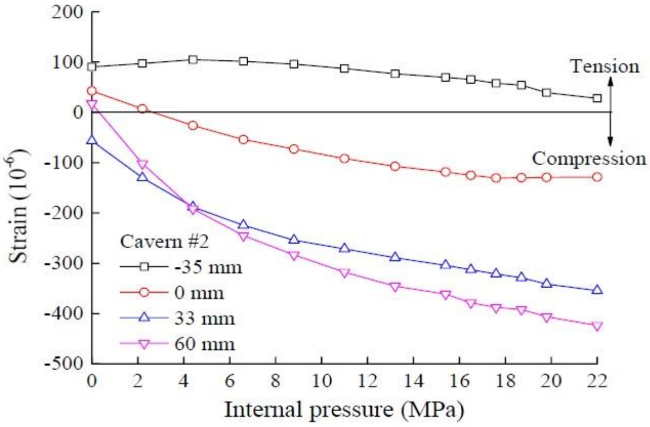
Fig. 6 Distribution of displacement against the internal pressure of cavern #2

3. Model test results

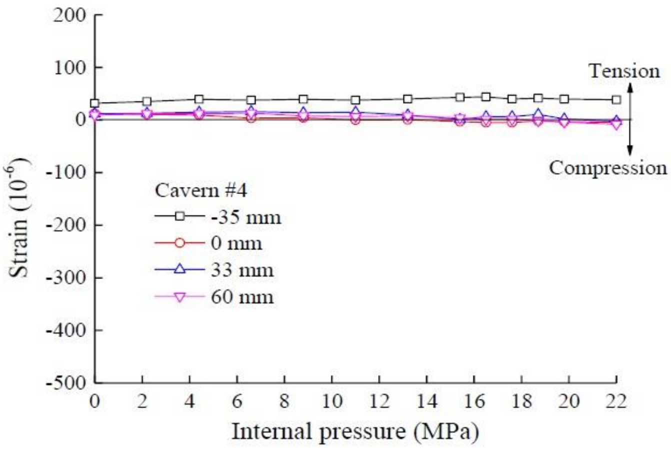
Fig. 6 shows the distribution of displacement against the internal pressure of caverns. The damage occurs and develops as a result of deformation of the caverns. It is deduced that as the difference in pressure between cavern #2 and the other caverns increases, the deformation of the caverns becomes large. Finally, damage increases when the cavern cannot tolerate the external load.



(a) Cavern#1



(b) Cavern#2



(c) Cavern#4

Fig. 7 Distribution of strain against the internal pressure of cavern #2

Fig. 7 illustrates the horizontal strain at measuring points originating from the internal pressure. It is observed that the largest strain occurs at cavern #2 followed by the adjacent cavern. Meanwhile, the smallest strain occurs at the diagonal cavern.

The obtained results demonstrate that the impact of pressure loss is limited to the cavern, in which the pressure is discharged. On the other hand, such effect on the other three caverns is negligible.

4. Conclusions

In the present study, salt rock gas storage caverns in Jintan, China are studied experimentally. The stability of the salt caverns is analyzed using a physical model. The obtained results reveal that the loss of the gas pressure increases the deformation around the cavern wall, thereby reducing the stability of caverns.

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