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Research Paper

Investigation of the Long-Term Stability of Salt Rock Cavern for Compressed Air Storage

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Abstract: Compressed air storage is one of the methods of energy storage. One of the most important parts of a compressed air storage system is the storage cavern. In this study, the behaviour and the long-term stability of the salt cavern as a storage site for compressed air were investigated. Due to the construction and operation of the salt cavern, the in-situ stress conditions around the cavern will change. The difference between induce stress and pressure of compressed air will cause the cavern to converge and damage around it. In this study, the salt rocks from one of the regions of Iran were used to test creep. To investigate the creep behavior of salt rock, creep test was performed in three stress levels in a stepwise manner. Lubby2 model parameters were calculated. Then, using LOCAS finite element software, the compressed air storage cavern was simulated and its behavior and stability were investigated. The results of these experiments and modelling have shown that with increasing stress in each stage, the slope of the secondary part of the creep increases. Therefore, it can be concluded that with increasing stress, the Maxwell viscosity coefficient decreases. In addition, the amount of movement in the lower half of the cavern was more than the upper half of it. Value of the cavern safety factor according to the Devries dilation criterion also decreased with increasing depth and the probability of dilation in the cavern wall increased.

Keywords: Compressed air storage, Salt cavern, Creep, LUBBY2 creep model, LOCAS software.

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INTRODUCTION

Large-scale compressed air energy storage (CASE) is a convenient way to balance the renewable energy used in electrical energy systems such as solar, wind and tide[1].

The compressed air energy storage system was first developed in Huntorf, Germany in the mid-1970s. A few years after the construction of this power plant, the first compressed air power plant was built in the United States. At present, both of these plants have successfully used the salt cavern for compressed air energy storage[2]. In this study, salt cavern was selected as a compressed air storage location due to its very low permeability, low construction cost and its use in two existing power plants [3].

After construction and during the operation of the salt cavern as a storage site, the in situ stress conditions around the cavern will change and will cause deviant stresses around the cavern. Deviation stress will cause the cave to converge and damage around it. Most studies on salt caverns have been on natural oil and gas storage caverns and less studied have focused on salt caverns on compressed air storage.

In this research, by performing creep experiments on samples of salt rock under three different stresses, the creep behavior of the salt rock has been studied step by step and then to investigate the stability of the salt cavern during construction and operation, simulation of cavern behavior has been performed. In a series of preliminary experiments performed by Habibi et al [4] on rock samples, the strength and elastic properties of salt rock samples have been determined. These data are shown in Table 1.

Table 1. Strength and elastic properties of the samples [4]

Uniaxial compressive strength (MPa)	Tensile strength (MPa)	Elastic modulus (MPa)	Poisson ratio
13.15	1.55	938	0.284

METHODS

Samples of rock salt

Salt rock samples have been tested for creep. Salt rock samples have been prepared according to the standards of the International Society of Rock Mechanics. The diameter of salt rock samples was 54 mm and the ratio of sample length to sample diameter was 2.5 to 2.79[5]Grade A or Deutsche Normen DIN 51 220, DIN 51 223, Klasse 1 and DIN 51 300. (b. Samples of rock salt used in creep experiments are shown in Figure 1.

Figure 1. Samples of rock salt

The rock has shown a transition from deformable to brittle behavior in the expansion zone. Consequently, increased damage in the dilation area leads to the opening of small cracks and increased permeability. For these reasons, the expansion boundary can be considered as a criterion to ensure the long-term integration of the cavern [6]. The most advanced measure of dilation was introduced by Devries [7]. To determine the viscoplastic properties of rock salt, stepwise creep test was used. The basic model used to study the deformation properties of salt is Lubby2 model. At the beginning of the experiment, the displacement was taken every few seconds, minutes, and over time, every few hours. Then, after the strain rate reaches a constant value, a new stress level (step) is applied to the sample and the strain measurement were repeated. Experiments have been performed under three levels of stress (steps). The specifications of the experiments are given in Table 2. Figure 2 shows the creep carve obtained from the experiment. The parameters of

Lubby2 model have been calculated using the creep test and presented in Table 3. It was also found that at each step of the creep test, the slope of the secondary creep curve has a direct relationship with the applied stress values; and with increasing the stress, the slope of the secondary creep curve increases and Maxwell viscosity coefficient values decreases.

Table 2. Specifications of uniaxial creep test

Step	Stress (MPa)
Step 1	8.5
Step 2	10
Step 3	11.5

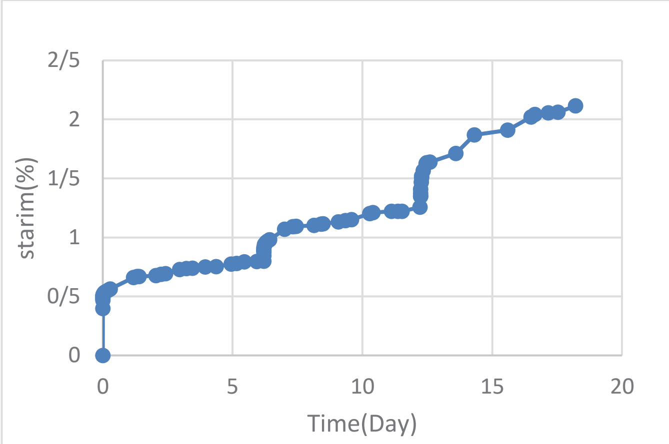

Figure 2. Creep curve obtained from the experiment

Table 3. Lubby2 Model Parameters

Sample	$\bar{\eta}^*_{M\sigma}(MPa.d)$	m(MPa^{-1})	$\bar{G}^*_k(MPa)$	K_1(MPa-1)	$\bar{\eta}^*_k(MPa.d)$	K_2(MPa-1)
STC1	4.4E4	-0.262	9.7E4	-0.42	1289	-0.038

Numerical modelling

Salt rock has a very complex behavior and therefore predicting the long-term behavior of this rock requires appropriate behavioral models, simulation and analysis of its behavior by a powerful software. In this study, LOCAS 2D finite element software was used for the salt cavern simulation.

Geological structure

The shape of the cavern considered as capsule shape with diameter of 42 m, a length of 150 m and overburden thickness of 650 m was considered.

Simulation of manufacturing and operation process

During the construction process, the pressure in the center of the cave decreased from the in-situ pressure (7.9 MPa) to 4.4 MPa (weight from the salt water column) at the end of the debrining phase and then to 6.4 MPa at the end of the leaching phase.

FINDINGS AND ARGUMENT

The rate of converge in the volume of the cavern can be considered as 0.68% per year, which is an ideal value and less than 1%, and reducing the volume of the cavern in these conditions is acceptable for the storage cavern. Examining the vertical displacement contour, it can be seen that the amount of displacement in the lower part of the cavern was more than the upper part of the cavern, which was a result of more deviatoric stress in that area. In the study of contour radial displacement, it was observed that most of the displacement is related to the lower half of the cavern (Figures 3A and 3B). By examining the contours of the cavern safety coefficient based on Devries (2005) dilation criterion in two pressures of minimum (4.6 MPa) and maximum (6.6 MPa), it was observed that all different parts of the cavern wall have a suitable and high safety factor. The value of safety factor in both contours decreased with increasing depth, which can be considered as a result of increasing the deviatoric stress following an increase in ground stress (Figures 3C and 3D).

CONCLUSION

Compressed air storage is one of the types of energy storage methods. One of the most important parts of this compressed air storage system is the storage site. In this study, the long-term stability of the compressed air storage cavern under cyclic loading was investigated. Using rock samples, uniaxial creep test was performed in three stages in a stepwise manner and then the results of the experiments were used for numerical analysis. The results are as follows:

With increasing stress in each stage, the slope of the secondary part of the creep curve increased, so it can be concluded that with increasing stress, the Maxwell viscosity coefficient decreased. Vertical displacement contour showed that the amount of displacement in the lower half of cavern was more than the upper part, so the stress difference was higher in that area and the roof tended to move down and the bottom of the cave tended to move up. The radial displacement contour showed that most of the displacement was related to the lower half of the cavern. Also, with increase in depth, the value of the cavern safety factor according to Devries dilation criterion decreased.

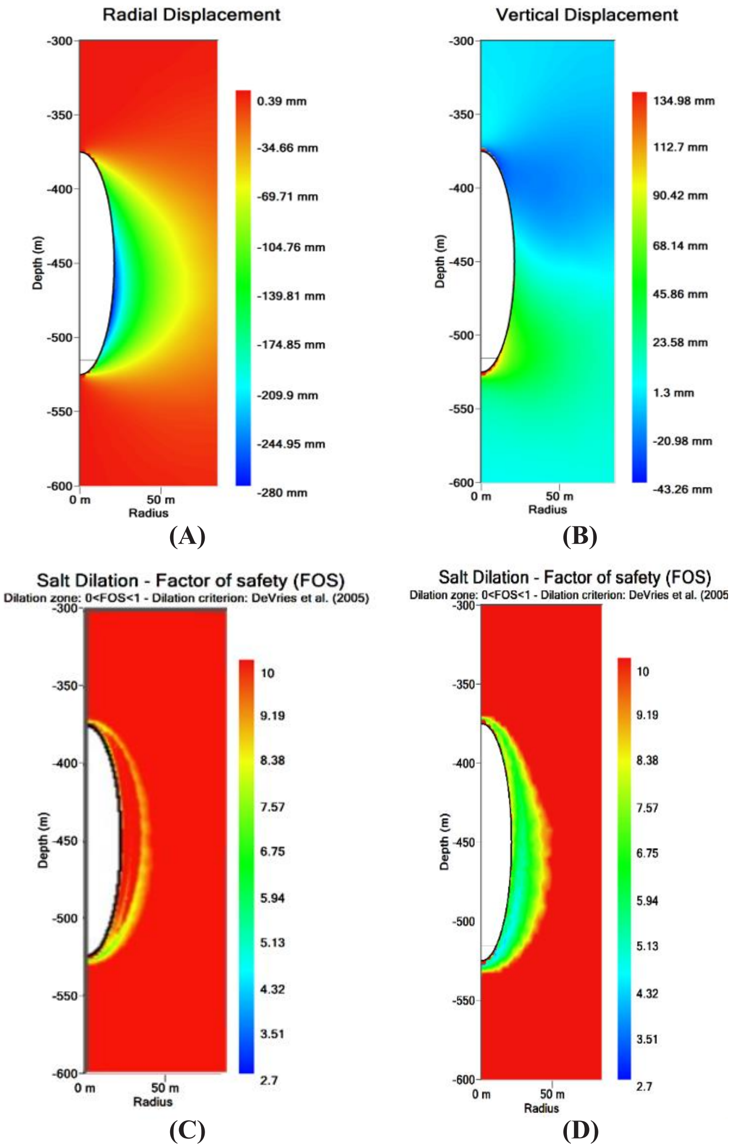

Figure 3. Displacement contour and safety factor contour of cavern according to Devries dilation criterion; **A:** contour of radial displacement, **B:** contour of vertical displacement, **C:** Contour of Devries dilation criterion at maximum pressure, **D:** Contour Devries dilation criterion at minimum pressure

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