Inverse Simulation for Salt Cavern Wall Collapse during Cycling Loading: A Field Case Study

Yi Zhang1 Wenjing Li2

1. Petroleum Exploration and Production Research Institute of SINOPEC, Beijing, China
2. State Key Laboratory of Geomechanics and Geotechnical Engineering, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan, 430071, Hubei, China

Abstract. Salt cavities used as underground gas storage have received increased attention for serviceability and sustainability considerations during gas cycling loading. However, traditional stability analysis overlooks the thermal effects induced by the operation and cannot predict the potential risk. In a field case in Jintan, Jiangsu Province of China, the thermal response to gas injection-and-withdrawal process of the walls of Cavern L was explored. A Bonded-Block Model (BBM) based on a 3DEC platform is proposed in inverse simulation for the field case’s cavity collapse process. By comparing the field case with simulation results, the proposed thermal-mechanical coupling model is validated for predicting the risk of cavity instability. The simulation results show that the thermal effect induces the collapse of the surrounding rock, that is, thermal tensile stress causes thermal cracks on the surface of the cavity.

1. Introduction

The salt cavern is the ideal medium for underground gas storage with 6~7 operating cycles per annum. When the salt cavern is in operation (i.e., filled with natural gas, compressed air, and hydrogen), the cavern’s stability is controlled by the internal pressure of fluid flow (Khaledi et al., 2016). The thermo-mechanical coupling effect resulting from gas pressurization or depressurization significantly alters the original stress field in the cavern walls, thus inducing severe deformation and eventual damage at some concave sections of the walls (Arson, 2020). Three aspects of major concern in solution salt rock mining include the influence of temperature variation, the evolution of stress, and the time-dependent convergence of cavern (Hunsche and Hampel, 1999). The fluctuation of internal pressure and temperature due to the gas injection-and-withdrawal process, temperature-dependent creep behavior of rock salt, and deformation associated with underground cavens are the prime challenges in the operation of salt caverns for gas storage purposes. The large temperature amplitudes of inner working gas may lead to tensile stresses and tensile failure in salt cavern walls (Böttcher et al., 2017). Low gas pressure ensuing from the gas withdrawal process tends to trigger the tensile stresses (Bérest, 2011); and the additional induced thermal tensile stresses may generate fractures at the wall and roof of a salt cavern (Bérest et al., 2014; Li et al., 2019; Serbin et al., 2015;). There are three grades of salt cavern instability: (1) block falls in parts of cavern, occurring mainly in the stage of solution mining and gas injection for the first time, and may impact the tubing; (2) the roof collapse and wall of salt cavern scatter; (3) the whole salt cavern fracture and fall apart entirely, although there is no potential risk of the block fall for some cases, however, for some specific zones, such as flat roofs with large span, it is more prone to develop fractures and collapse due to thermal tensile stresses (Bérest et al., 2014). Therefore, it is crucial to investigate the stability and serviceability of salt caverns considering thermal-mechanical coupling effects.

Conventional stability analysis using FLAC3D primarily focuses on evaluating plastic zone, deformation, convergence, etc. (Hu et al., 2020). However, this method fails to analyze the coupling effects of thermal-mechanical changes, and thermal effects induced by the operation have been overlooked and cannot predict the potential risk. In the numerical simulation analysis for cavern stability, selecting a constitutive model for the creep behavior of rock salt has become a priority (Azabou et al., 2021). The influence of temperature should be included in the numerical model as the creep characteristics are time and temperature-dependent. Also, the thermo-dynamic problem in salt cavern operation aroused more concerns in industry. The causes of collapse accidents and the thermal effects
induced by the cycling loading should be investigated for salt cavern stability and optimal design operation parameters.

This study aims to thoroughly investigate the evolution of thermal damage in salt caverns subject to typical thermo-mechanical storage conditions (gas cycling loading) in a field case. First, this paper proposes modeling procedures of coupled thermo-mechanical methodology associated with gas injection-and-withdrawal in an underground salt cavern. Then the engineering problem is introduced, and series of simulation works are conducted to investigate the thermal effects alongside the mechanisms contributing to the collapse. Finally, the thermal damage evolution of field case Cavern L is analyzed.

2. Description of a field case

Jintan Salt Cavern Gas Storage is a supporting project of the great West-to-East Pipeline Project. It is also the first and most extensive underground gas storage group of salt caverns in China, Jiangsu Province, perhaps the largest one in Asia. It handles the gas peak shaving in Yangtze River Delta region and is still under construction. Cavern L is one of the salt caverns for underground gas storage in Jintan. Cavern L leaching began in 2005. In 2009, Cavern L finished leaching, and the remaining brine has been replaced by injected gas. In 2010 its use as a gas injection-and-withdrawal facility began. Two sonar measurements were conducted, before its use, in 2009 and later in 2015. A comparison between these sonar results demonstrated a displacement variation at the top roof of the cavity to a maximum distance of 4m (shown in Figure 3). Thus, providing enough basis to suspect that there is a fall of blocks of the cavern wall. However, the conventional stability analysis shows that Cavern L should be in stable condition during the first 5 years of operation, and there is no risk prediction before the accident. Therefore, the damage evolution and the exact dynamic process are unknown. This study demonstrates Cavern L’s analysis to investigate the thermal-mechanical coupling effects on cavern stability. Additionally, a series of numerical simulation cases based on the thermal-mechanical coupling model explores the collapse influencing factors.

Figure 1 illustrates the target research objective Cavern A from Jiangsu Jintan underground gas storage in this study, showing the sonar results, the 3D visual shape of the salt cavern. As the collapse occurs at the cavern roof, a quarter section of the salt cavern is selected in the following simulation works.
Figure 1. Geometric model dimensions Sonar results of Cavern L in 2009, and 2015, respectively. (Li et al., 2021)
3. Inverse simulation approach for analysis of collapse

3.1 Model configuration

The rock salt mass is represented by Bonded-Block Model (BBM) (Vlachopoulos snf Diederichs, 2009; Gao et al., 2016) the geometry and rock properties used in this study shown in Figure 2, and Table 1, respectively. The block contacts is the key parameters in model calibration, the tensile strength in the contacts follows the Gaussian Distribution. The Figure 2 demonstrates the tensile stress distribution.

![Figure 2. Geometric model dimensions](image)

Table 1. Simulation parameters in 3DEC model

| Parameters                      | Units    | Values          |
|---------------------------------|----------|-----------------|
| Young’s modulus                 | GPa      | 30/15/6.5       |
| Poisson’s ratio                 | /        | 0.3             |
| Density                         | kg/m³    | 2160            |
| thermal Conductivity            | W/m·°C   | 6.5             |
| specific heat                   | J/kg·°C  | 880             |
| linear thermal expansion coeff. | °C⁻¹     | 5×10⁻⁵          |
Figure 3. Distribution of tensile strength at block contacts.

### 3.2 Simulation scheme

| Categories | Retain Pressure/MPa | Retain Time/Time step | Thermal Effect |
|------------|---------------------|-----------------------|----------------|
| Case 1     | 9.5 / 8.5 / 7.5 / 6.5 | 20000 / 40000 / 60000 | √              |
| Case 2     | ——                  | ——                   | ×              |
| Case 3     | ——                  | ——                   | √              |

Three simulation cases (see Table 2) are conceived in this study to investigate the salt cavern wall thermal-dynamic response to the gas injection-and-withdrawal process. Case 1 is employed to verify the validation of the proposed BBM model in 3DEC and compare the simulation results with the sonar results in 2015; by comparison between Case 1 and Case, the influence of thermal effect has been investigated for salt cavern wall stability. Case 3 is developed for thermal effect mechanisms, i.e., temperature drop contributions to cavern wall during gas depressurization.

### 3.3 Simulation Results

Simulation results of Case 1, presented in Figure 4, show the thermal damage at the cavern roof. There is a 4 m variation of displacement, which is consistent with the sonar results in 2015. Thus, the thermal-mechanical modeling predicts the thermal damage evolution around the salt cavern during gas cycling loading.
Figure 4. The inverse simulation of the collapse process is compared with the sonar result of 2015.

Investigating the impact of temperature drop on the salt cavern wall, in Case 3, the inner pressure variation in the cavern wall was nullified. Thus, with constant pressure as the initial condition, the temperature variation was set as boundary condition; the thermal stress is computed after a particular temperature drop, and the thermal effects observed.

Figure 5. Case 3 Simulation Results (1)

Figure 5 illustrates the parts of the simulation results of Case 3, in the upper figures, the different color represents the discrete blocks, and the broken contacts between the blocks. The lower three figures show the stress contour, from left to the right, the time-step is 2, 10, and 30 respectively after the temperature drop finished.
Figure 6 illustrates the rest of the simulation results of Case 3. The upper figures are the block contact displacement illustration, whereas the lower figures are the block displacement illustration. As shown in the figures, the tension area occurs at the beginning of the computation, the cracking area induced by the thermal stress is consistent with the temperature influence area. However, due to the limitation of the configuration of the blocks, which is a regular tetrahedron, and the block can not be segmented, the propagation path of the thermal cracking can not represent the actual cracking path. With the computation time-step, the energy released during cracking development and the tension at the cavern wall is disappeared. As a result, the fracture propagation makes the blocks fall apart. With the retention time of the low-pressure operation, the fracture development is aggravated, and the cavern wall collapsed eventually.

4. Discussions
During the end of the gas withdrawal process and the subsequent conversion period from injection to the withdrawal process, low pressure in the cavity induce crack propagation. Eventually, the surface rock layer is broken and spalls. Thus, the analysis of the field case confirmed the impact of thermal-mechanical effects on the operation of the salt cavern, and the approach used in this study can optimize long-term operation parameters.

5. Conclusions and suggestions
A BBM based on a 3DEC platform is used in an inverse simulation for the cavity collapse process of a field case. The proposed thermal-mechanical coupling model is validated to predict cavity instability risk by comparing the field case with simulation results. The results show that the thermal effect induces the collapse of the surrounding rock, that is, thermal tensile stress causes thermal cracks on the surface of the cavity. The findings of this study have more practical applications in the stability analysis for salt caverns used as underground gas storage. Further analyses are required to confirm the influence of thermal-mechanical effects induced by gas pressurization and depressurization based on field cases, and to develop optimal design parameters for long-term salt cavern operations.
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