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Allowable pillar width for bedded rock salt caverns gas storage

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ABSTRACT

Three-dimensional numerical models of bedded rock salt cavern gas storages of Jintan salt mine, Jiangsu province, China, are established using $FLAC^{3D}$ simulator to investigate factors affecting the allowable width for pillars between two adjacent caverns. Vertical stress, deformation, plastic zone, safety factors, and seepage pressure of pillars between two adjacent salt caverns are discussed, and the allowable width of the pillars is optimized. Results show that the vertical stress on the pillars increases with depth and decreases with increasing pillar width, gas pressure inside the caverns, and creep time, i.e., cavern operating duration. Rock salt creep gradually smoothens the vertical stresses on the pillars, and the effect is expected to become imperceptible after five years. An increase in gas pressure difference between the caverns increases shear stresses in the pillars, which aggravates the unevenness of stress distributions and reduces the stability of the pillars. The asynchronous injection–production mode has negative effects on pillar stability and seepage pressure, particularly for narrow pillars. Interlayer permeability and pillar width are key factors affecting seepage through the pillars. The allowable pillar width for bedded salt cavern gas storage groups in Jintan salt mine, Jiangsu province, China, is proposed based on vertical stress, deformation, plastic zone, safety factors, and seepage pressure, and is recommended to be 2.0–2.5 times the maximum diameter of a cavern. This is a smaller range than the pillar width proposed by available codes, which ranges from 1.5 to 3.0 times the maximum diameter of a cavern. This decreases the uncertainty in the pillar width design caused by the conventional wide range and can increase the efficient use of the rock salt resources. The study provides fundamental data and references for designing pillars for salt cavern gas storages in other areas with similar conditions.

1. Introduction

An underground salt cavern is recognized as one of the most efficient and economical methods to store hydrocarbon energy sources, such as natural gas, petroleum, and ethylene (Evans, 2007; Raju and Khaitan, 2011; Wang et al., 2011; Niklas et al., 2012; Wang et al., 2013). Such storage is suited for short-term storage of natural gas because it allows high deliverability and makes it possible to switch rapidly from injection to withdrawal. Therefore, salt cavern gas storage is increasingly used throughout the world. For example, 23% of the total natural gas underground storage in America was contributed by salt cavern gas storage in 2011 (Salt caverns account for 23% of U.S., 2014). The British government constructed or reconstructed more than 20 salt caverns for storing natural gas in 2010 to improve the safety of its energy supply (Wang, 2011). In constructing salt cavern gas storages, appropriate pillar width plays an important role in ensuring the safety of the caverns and in improving the efficient use of rock salt resources. If a pillar is too wide, salt resources are wasted and economic benefits decrease. If a pillar is too narrow, failures of pillars and cavern roofs may occur. In extreme cases, even an entire salt cavern group may fail.

China has plenty of rock salt resources, primarily salt beds. According to geological exploration, salt beds can provide all the conditions required for constructing underground gas storages. The construction of gas storages has generated significant interest in engineering research because of the demands for energy security in China (Wang et al., 2010, 2012a). However, given the relatively thin nature of the salt beds and the presence of alternating other sedimentary rock formations, i.e., anhydrite, shale, and glauberite (Wang et al., 2010, 2012a, 2012b), problems regarding pillar design for salt cavern gas storages located in salt beds are more challenging than those for caverns located in salt domes. Fig. 1 presents a diagram of an underground salt cavern gas storage group in layered salt formations. This salt cavern gas storage group is composed of

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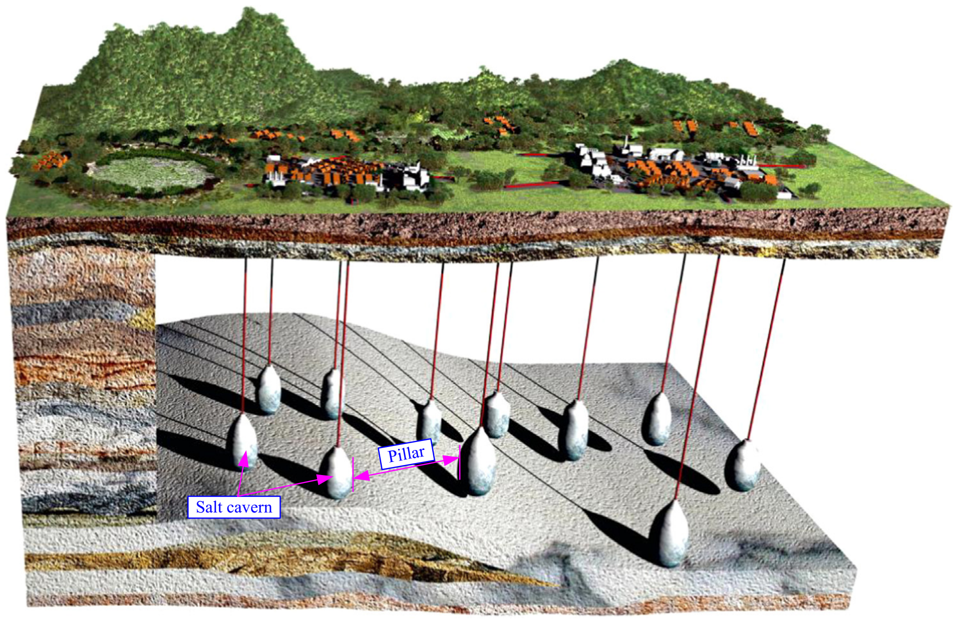

Fig. 1. A diagram of an underground salt cavern gas storage group in bedded salt strata.

numerous individual caverns. Salt caverns may interact, thus requiring a comprehensive design. Pillar width is affected by numerous factors, such as the strength, creep parameters, and gas flow resistance of the rock salt and the interbedded rock, salt cavern dimensions, operating parameters, and failure criteria. Therefore, pillar width design is a critical issue in the design of salt cavern gas storage groups.

A large number of studies on pillar design in related fields, e.g., coal mines, iron mines, and underground limestone quarries have been conducted. In the 1970s, Wilson (1972, 1977, 1981) studied the stresses and stability of coal mine pillars. Waltham and Chorlton (1993), Waltham and Cubby (1997), and Waltham and Swift (2004) constructed a coupled roof and pillar model to evaluate the stability of pillars between iron mine caverns in Nottingham, England. Zipf and Mark (1997) investigated the violent collapse mechanism of large room-and-pillar mines. They proposed a theoretical design criterion to prevent violent pillar failure (Zipf and Mark, 1997). Esterhuizen and Iannacchione (2005) investigated the failure mechanism of pillars in underground limestone quarries and found that horizontal tectonic stresses cause intact rock failure. However, because of typical rock salt creep, the differences in properties between rock salt and non-salt layers, as well as allowable plastic deformations, the aforementioned calculating models and methods cannot be used directly in designing pillars for bedded rock salt cavern gas storage.

A number of useful studies evaluating the stability of salt caverns and pillars have been conducted. Mirza (1981) studied creep deformation of rock salt pillars. Hoffman (1993) proposed a three-dimensional (3-D) finite model using JAC^{3D} software to evaluate the effect of pillar width on the stability of gas storage caverns in salt domes. Staudtmeister and Rokahr (1997) proposed a guideline for designing cavern shape and pillar width. Van Sambeek (1997) and Frayne and Van Sambeek (2002) established a salt pillar design equation and validated it by comparing the result of the equation with numerical results. Martin et al. (2004) discussed the influence of three rock salt creep constitutive laws on the stresses and deformations of caverns and pillars. Swift and Reddish (2005) investigated stress and deformation distributions of rock masses surrounding salt caverns and provided safety factors based on the Mohr–Coulomb failure criterion. Sobolik and Ehgartner (2006) presented 3-D models based on a close-packed arrangement of 19 caverns, and analyzed these models using a simplified symmetry involving a 30° wedge portion of the model. These studies mainly focused on the stress, deformation, and failure mechanism of pillars and salt caverns. The quantitative effects of the injection–production cycle, pillar width, depth, gas pressure, creep time, pressure difference among adjacent caverns, and other factors, on the stress, deformation, plastic zone, safety factors, and seepage pressure of pillars have rarely been studied systematically. Above research results show the stability assessment of pillars is a complicated problem, which is influenced by many factors. Therefore, how to precisely evaluate the pillar stability remains a key issue in this engineering field.

Gas seepage has significant effects on the safety of caverns in salt beds according to available literature. Chen et al. (2009) found that the different properties and different deformations of salt and non-salt layers can cause natural gas leakage during the operation of a bedded salt cavern gas storage. These researchers proposed a model for predicting the limit on the gas pressure to prevent a salt cavern from leaking. They also pointed out that gas seepage in an interlayer is detrimental to pillar stability. Yang et al. (2009) studied the relations between gas seepage pressures and the parameters of the interfaces between salt and non-salt layers. The sealing of West-1 and West-2 bedded salt cavern gas storages of Jintan salt mine, Jiangsu province, China, was evaluated using the model. The results of the research showed that the stress state of the narrow pillar was significantly affected by gas seepage.

In the present study, FLAC^{3D} simulator is used to establish 3-D numerical models of bedded salt cavern gas storages of Jintan salt mine, Jiangsu province, China. The effects of the synchronized and asynchronous injection–production modes, pillar width, depth, gas pressure, creep time, and pressure difference among adjacent caverns on the vertical stress, deformation, plastic zone, safety factors, and seepage pressure of a pillar between two adjacent salt caverns are discussed. Accordingly, the allowable pillar width is proposed. The obtained results provide fundamental data and references for designing pillars for bedded rock salt cavern gas storages.

2. Modeling approach and process

In this study, a 3-D model for two adjacent underground salt cavern gas storages of Jintan salt mine in China is established using