PETROLEUM EXPLORATION AND DEVELOPMENT
Volume 44, Issue 1, February 2017
Online English edition of the Chinese language journal

Available online at www.sciencedirect.com
ScienceDirect

Cite this article as: PETROL. EXPLOR. DEVELOP., 2017, 44(1): 139–145.

RESEARCH PAPER

Solution mining technology of enlarging space for thick-sandwich salt cavern storage

ZHENG Yali[1, 2, *], ZHAO Yanjie[1, 2], DING Guosheng[1, 2], WU Zhide[1, 2], LU Shouquan[3], LAI Xin[1, 2], QIU Xiaosong[1, 2], YANG Dong[4], HAN Bingjie[1, 2], WANG Lingxin[5]

1. PetroChina Research Institude of Petroleum Exploration & Development-Langfang Branch, Langfang 065007, China;
2. CNPC Key Laboratory of Oil & Gas Underground Storage Engineering, Langfang 065007, China;
3. PetroChina East Pipeline Co., Ltd., Shanghai 200122, China;
4. Foreign Cooperation Department, PetroChina, Beijing 100007, China;
5. The Second Mud Logging Company of CNPC Bohai Drilling Engineering Company Limited, Cangzhou 062552, China

Abstract: Aiming at the current problem that thick sandwiches are commonly developed in domestic salt mines, this study investigated whether thick sandwiches would collapse to allow connection of salt deposits above and below, consequently expand single cavern capacity by laboratory experiments, numerical simulation and field tests. The analysis of water-soluble mechanism and changing patterns of mechanical parameters of sandwich layers after water immersion shows that: after water immersion, sandwiches dissolve into honeycomb structure with cracks that easily flake, and the residues occupy small space; after water immersion, mechanical strength of sandwiches decrease greatly, susceptible for failure and collapse. Based on the calculation model for critical limited span, the collapse timing was predicted. In addition, laws of thick sandwiches' collapse were obtained by numerical simulation, which indicate that the smaller thickness, as well as the larger depth, limited span and storage height of the sandwiches are more likely to cause the sandwich collapse. The design idea of "full immersion and secondary cavity construction" was proposed, and cavern leaching design for a 12 meter thick sandwich in a gas storage was made, and tests on two wells were conducted. The results prove that thick sandwiches could collapse, increasing leaching height and single cavity capacity, and the technology is technologically and economically feasible.

Key words: salt-cavern storage; thick sandwich; water-soluble mechanism; mechanical parameter after water immersion; critical span; cavern leaching design; cavern leaching experiment

Introduction

Foreign countries have begun to utilize salt caverns for underground gas storage since the 1950s[1]. With the startup of "West-to-East Gas Transmission" project, domestic researchers initiated study on salt cavern storage, and elaborated technologies of storage construction and solution mining through reviewing foreign literatures[2–4]. Regarding solution mining with sandwich collapse, taking multilayer sandwiches less than 10 m in Jintan salt mine as example, researchers investigated how to control sandwich collapse in order to avoid casing bending and damage, as well as localized necking in cavities and so on[5–11], and suggested that gas storages should be constructed in the geological condition with thin and less sandwiches[5]. Currently, thick sandwiches more than 10 m are common in all salt mines surveyed for possible gas storage construction except for Jintan. In the past leaching design, thick sandwiches were not considered, which would definitely decrease leaching height. However, if thick sandwiches can be dissolved to connect salt layers above and below, leaching height would be increased and individual cavern storage capacity would consequently be expanded. In this study, the feasibility of expanding storage space by dissolving thick sandwich is discussed from aspects of water-soluble mechanism, changing laws of mechanical parameters after water immersion, and collapse prediction, in combination with field test results.

1. Water soluble mechanism

Deposited in salt lake environment, thick sandwiches in salt formation are with certain amount of NaCl. For example, rock composition analysis of samples taken from the 12 meters thick sandwich in a salt mine shows that NaCl content at the bottom and top of the sandwich ranges from 15% to 25%, and that of the middle part is about 5%. Water soluble experiments

Received date: 25 Apr. 2016; **Revised date:** 20 Dec. 2016.
*** Corresponding author.** E-mail: zyl69@petrochina.com.cn
Foundation item: Supported by the Petrochina Science and Technology Major Project (2015E-4002).

were conducted on a lot of samples taken from the sandwich, experiment results of three representative samples (Table 1) show that sample yp001 at the top and sample yp002 in the upper part, glauberite mudstone, suffered dissolution to various extent and dissolved into honeycomb structure two weeks later through upward and lateral solution experiments. Sample yp001 is higher in water solubility. While sample yp003 in the middle part, brown-red mudstone, is lower in water solubility, only salt-bearing part dissolved into porous and crack structure.

Glauberite mudstone sample were completely immersed in water: after 7 days, honeycomb structure emerged on the surface; on day 17, granular matter appeared at the bottom, and suspended after shaking; on day 32, flaky exfoliation could be observed; on day 58, blocky mudstone emerged; on day 90, one fifth of the samples flaked off. Plus, due to differential dissolution, saliferous stripes in the sample cracked and intensified exfoliation. Therefore, after some period of immersion, muddy sandwich would break and be easy to collapse.

2. Changing law of mechanical parameters after water immersion

Water immersion experiments were made to find out changing laws of mechanical properties with time during leaching. Two types of immersion liquids, saturated brine and fresh water were used, brine immersion time was 28 and 33 days, and fresh water immersion time was 60 days.

The results (Table 2) show that non-immersed sandwich surfaces are resistant to break and have less effect on salt rock, while sandwich surfaces after immersion are easy to break, especially when the sandwich is tilted, sliding is likely to happen along the interface. Also, the sandwich containing halite and glauberite would be easier to fail than pure salt and glauberite. In addition, compressive strength of sandwiches would decrease with immersion time, which is highly correlated with water-soluble mechanism: more soluble substance, such as NaCl, would dissolve with immersion time, giving rise to abundant pore volume and mechanical strength loss. In contrast with saturated brine, fresh water has better dissolution condition, causing higher loss of mechanical strength. In other words, fresh water or low concentration brine should be employed to better decrease mechanical parameters, and accelerate sandwich collapse.

3. Collapse prediction

3.1. Prediction of critical span for collapse

With the continuous dissolution of salt deposits from below during leaching, poorly soluble sandwiches would gradually be exposed in brine. At an early stage, sandwiches suspend stably As leaching diameter increases, when the span reaches a certain value, namely, critical span, the sandwich would be subject to crippling under the influence of stress redistribution and mechanical strength reduction[7], thus leading to large-scale collapse. Therefore, collapse timing can be predicted by calculating the critical span.

Considering axisymmetric shape of a cavern and smaller leaching string size compared with the cavern diameter, sandwich in suspending state is simplified as a non-porous homogeneous circular plate[6]. Stresses on a sandwich include the pressure from brine, radial formation pressure, and its own gravity. Due to strong rheological property of salt, radial stress is considered to be uniformly distributed along the circular[6]. Based on this simplified model, Shi et al.[6] applied elastic shell theory and carried out analysis of critical stress for collapse, taking into account the effect of vertical force and horizontal force on the sandwich; mathematical model of critical stress for collapse has been established and prediction model of critical span for collapse has been obtained accordingly.

$$D = 2h\sqrt{\frac{1.224E}{K\sigma\left(1-\mu^2\right)}} \tag{1}$$

where D—Critical stress for sandwich collapse, meter; h—Thickness, obtained from drilling or logging data, meter; E—Elastic modulus, measured by rock mechanics laboratory experiments under the condition of brine immersion, MPa; K—Correction factor, in consideration of heterogeneity (thickness, composition) with regard to different position of a sandwich, and the value is a positive number more than 1 according to geological conditions[6]; σ—Radial formation pressure at the depth of a sandwich, acquired by logging, field tests etc., MPa; μ—Poisson's ratio, measured by rock mechanics laboratory experiments under the condition of brine immersion.

Taking a gas storage with thick sandwich as an example, the thickness of the sandwich is 12 m, radial formation pressure is 35 MPa, elastic modulus and poisson's radio measured through experiments are 0.748 GPa and 0.32, as a result, the critical span obtained is 11 m by using the above prediction model.

3.2. Prediction of thick sandwich collapse laws

Whether sandwich could collapse is closely related to sandwich thickness, burial depth, and span etc. On the basis of laboratory experiment on collapse mechanism, collapse laws was predicted by numerical simulation. With salt formation in a gas storage as reference, a simulation model was built assuming that the salt formation was under hydrostatic pressure. The center of the sandwich was the coordinate origin of the model, relevant horizontal and vertical displacement were constrained by side face and subface, and even load equal to rock gravity above the model was applied on the upper surface.

The simulation suggests that collapse generally begins at the center and margin of the sandwich: the central broken zone presents a tendency of divergent extension from the center to the edge and upper part, whereas the marginal broken zone shows a tendency of convergent extension from the bottom to the top of the edge initially and then from the bottom and the top to the inner edge and the center simultaneously.