International Journal of Rock Mechanics & Mining Sciences 73 (2015) 175–183

Contents lists available at ScienceDirect

International Journal of Rock Mechanics & Mining Sciences

journal homepage: www.elsevier.com/locate/ijrmms

Failure analysis of thick interlayer from leaching of bedded salt caverns

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ARTICLE INFO

Article history:
Received 21 May 2014
Received in revised form
8 October 2014
Accepted 5 November 2014
Available online 29 November 2014

Keywords:
Bedded rock salt
Interlayer
Failure analysis
Experiment
Theoretical analysis
Numerical simulation

ABSTRACT

A mathematical model is proposed to calculate the critical collapse span of a thick interlayer during the leaching of a gas storage salt cavern in bedded rock salt. In the proposed model the ratio of the height of the damaged zone to the interlayer thickness is introduced. This approach overcomes the negative effects on the calculation accuracy of the fact that the damaged rock does not fall off from the thick interlayer but is linked to it by contact forces. Brine immersion tests have been carried out to obtain the solution characteristics and the influence of brine immersion on tensile strength and on elastic modulus of interlayer samples of a salt formation from Yingcheng city, Hubei province, China. Experimental results show that these mechanical parameters decrease with immersion in brine and more so with decreasing brine density. To validate the proposed model, a 3D geomechanical model has been built of a salt cavern under construction in a bedded rock salt formation of Yingcheng city. The stresses and deformations of the thick interlayer obtained by the analytical solution and by the numerical simulation are compared, and show good agreement. The critical collapse span of the thick interlayer decreases greatly with a decrease of the ratio of damaged zone height to interlayer thickness and interlayer depth, increases with increasing tensile strength and thickness of interlayer, and is independent of the elastic modulus of the interlayer. The proposed model has been used in the planning of the leaching of the underground salt cavern gas storage of Yingcheng city, Hubei province, China.

1. Introduction

Rock salt caverns serve as one of the best underground methods to store energy, and can be located in a salt dome or in a bedded deposit [1–5]. According to the questionnaire results of Solution Mining Research Institute in 2009 [6], approximately 50% of the energy stored in rock salt mines (oil and gas) is stored in bedded deposits and 50% in salt domes. Rock salt in China is primarily bedded, usually composed of many salt layers and interlayers (e.g. anhydrite, mudstone, and glauberite). These interlayers are difficult to dissolve in water, and have a wide range of thicknesses [2,4,7,8]. Water solution mining with single well convection is widely used to leach salt caverns serving for underground gas storage (UGS) [9]. This method can be carried out easily in salt domes because of their large height and high mineral grade. Caverns with ideal shape can be leached, and have good stability. However, insoluble interlayers pose many challenges to this construction method in bedded rock salt formations [10–12], especially when thick interlayers may become the key factor in the cavern design and leaching.

Fig. 1 presents a schematic diagram of a cavern leached by water solution mining with single well convection. Fresh water or unsaturated brine is injected into the cavity through the inner leaching tube (or through the annulus between the inner and outer leaching tubes), and high concentration brine is ejected to the surface through the annulus between the inner and outer leaching tubes (or through the inner leaching tube). Rock salt around the cavity is dissolved by the unsaturated brine, and the cavity gradually increases in size. Oil is injected into the cavity to control the solution rate of rock salt around the cavity top and to form an ideal cavern shape. However, insoluble interlayers impact the flow distribution and decrease the brine flowing speed in the areas around them. This causes the salt dissolving rate to decrease greatly, and makes the cavern shape control difficult. Moreover, a sudden collapse of an interlayer during the leaching may damage the tubing and casing and may cause other accidents. Damage of the leaching tubes

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http://dx.doi.org/10.1016/j.ijrmms.2014.11.003
1365-1609/

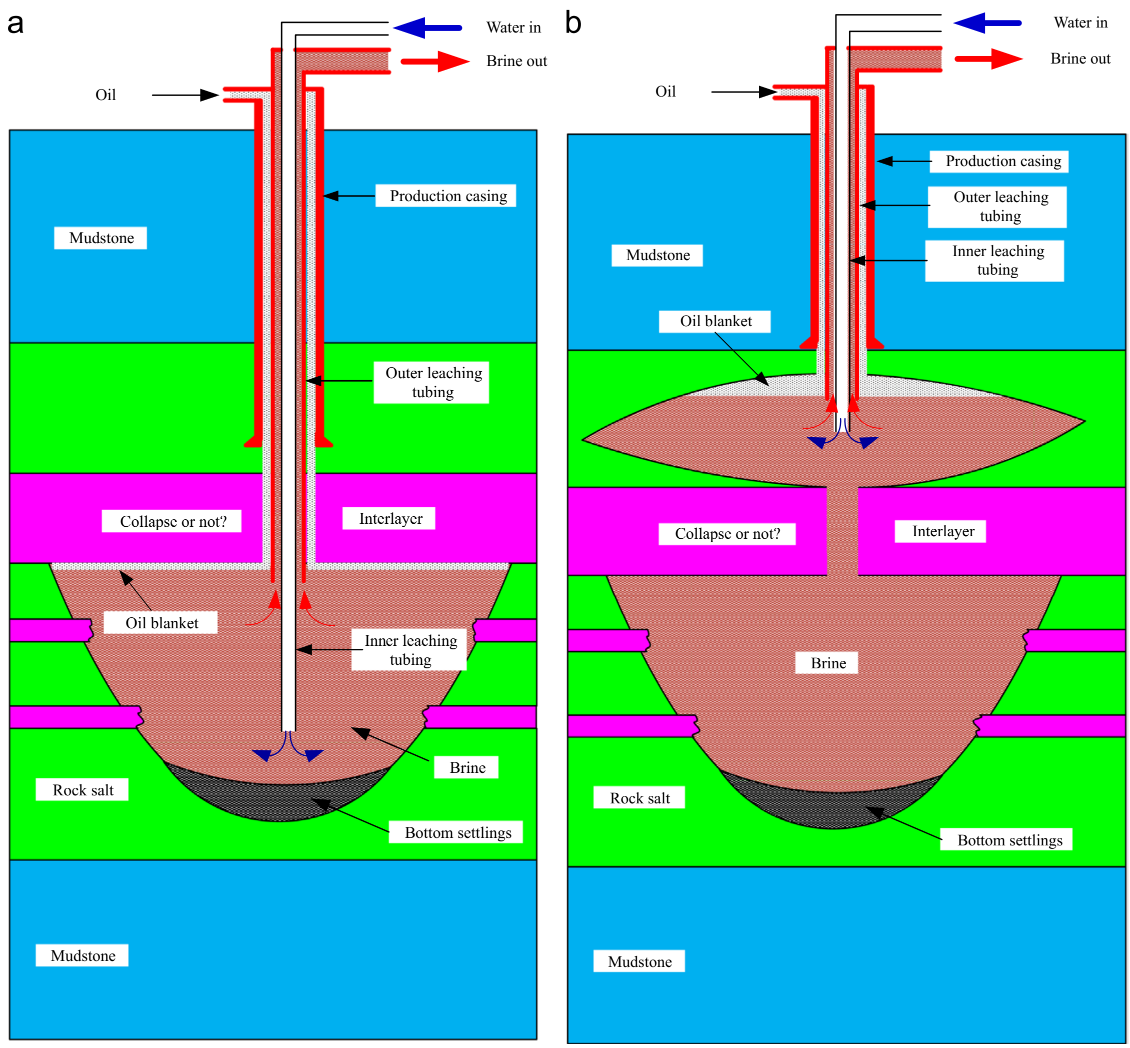

Fig. 1. Schematic diagram of cavern leaching by water solution mining with single well convection method in bedded rock salt formation. (a) Cavern intersected by thin interlayers only. (b) Cavern intersected by a thick (and thin) interlayers.

changes the depths of water outlet and brine inlet causing an irregular cavern shape. On the other hand, the interlayer may not collapse during the leaching when its thickness is relative large (>4 m). This will constrain the cavern volume and will decrease the gas storage capacity. As the leaching time increases, the thick interlayer becomes a vulnerable suspended structure, as shown in Fig. 1b. Due to the solutioning of the salt above and underneath the interlayer, the entire interlayer is immersed in brine, and as a result its mechanical parameters (such as tensile strength and elastic modulus) decrease. Moreover, the forces to which the interlayer is subjected increase as the suspended span grows. Ultimately, the thick interlayer may suffer a massive collapse, and a large cavern is leached. However, how to precisely predict the critical collapse span of a suspended thick interlayer is a difficult problem. First, local damaged rock masses do not fall off from the thick interlayer immediately when the stresses reach their tensile strength but connect together, maintaining some load bearing capability as the pressure arch effect forms in the thick interlayer. Second, the forces, including in-situ stress, dead load, and brine pressure difference to which the thick interlayer is subjected compose a complicated system. Therefore, study of the failure analysis of interlayers in the leaching of underground salt caverns in bedded rock salt formation is very necessary and valuable.

Many researches have been carried out on the effects of interlayers on the mechanical parameters of rock salt and on cavern stability. Studies on the influence of interlayer collapse on the cavern leaching are still rare. Bauer et al. [13] studied the roof stability of long horizontal leached caverns in bedded rock salt formations, and built a cantilever beam model to calculate the stresses in an interlayer. They thought shear and tensile failure were the main reasons causing roof instability. The influences of horizontal in-situ stress and of interlayer thickness are not included in their model. Charnavel and Lubin [10] investigated the effects of insoluble interlayers on cavern shape. They pointed out that the insoluble interlayers caused many cavity bottle necks and that the broken insoluble interlayers fell on the center cavity floor, forming a raised bottom. As a result the brine could not be expelled from the bottom and the cavern effective working volume decreased. Roland and Wim [14] discussed the influences of brine removal on the ground subsidence and listed several failure modes of interlayers serving as the cavern roof, such as tensile failure, shear failure, crushing rupture, and plastic yield. Michael and Maurice [15] simplified the interlayer at the cavern roof as a composite beam structure to determine the minimum operating pressure, and also studied the deformation and stress of the composite beam structure. Shi et al. [11,12] proposed a mechanical model to analyze thin interlayer collapse during the cavern leaching. They discussed local and overall buckling collapse mechanics. Because of the lack of considering the failure characteristics of thick layers, above models cannot be directly used for thick interlayer collapse prediction.