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ORIGINAL ARTICLE

Collapse mechanism of the overlying strata above a salt cavern by solution mining with double-well convection

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Abstract

In solution mining of salt formations, unreasonable salt cavities formed may lead to surface collapse hazards. In this paper, a mathematical model was proposed to analyze the collapse mechanism of the overlying strata above a salt cavern induced by solution mining with double-well convection. In the proposed model, the collapses of the overlying strata were supposed to occur layer by layer, and a thin plate with four edges clamped was introduced to calculate the critical collapse span of each layer. The limit breaking distance of the thin plate can be solved by setting the corresponding surrounding condition. According to the solution, the limit breaking distance is related to the dimensions, the mechanical properties of the rock, the buried depth, and the force status. For the convenience of calculation, a span criterion was introduced to distinguish the limit breaking distance. To keep the immediate roof more stable, the span criterion should be larger. As a case study, the collapse incidents at Dongxing Salt Mine were analyzed by the proposed model, and the collapses were verified to be inevitable under its mining and geological conditions. Discussions were finally carried out to study the influences of the thickness of the immediate roof, tension strength, Poisson ratio, and buried depth on the collapses. Above all, the collapses will occur more easily with the decrease of the thickness, tension strength, and Poisson ratio of each stratum. Especially, the collapse depth will not increase linearly with the buried depth, because of the bulking effect of the overlying strata.

Keywords Collapse of the overlying strata · Solution mining · Double-well convection · Thin plate model · Limit breaking distance

Introduction

Solution mining is the process of extracting soluble minerals (Johnson 1998, 2005, 2008), such as salt or potash. The method includes single-well convection and double-well convection. Thereinto, double-well convection (Fig. 1) is used widely because of its large production capacity and improvement of the recovery rate, especially in bedded salt formations. Solution mining of bedded salt formations or salt domes typically entails creating one or several large underground cavities that are filled with brine (Shi et al. 2015). The dimensions of cavities are based largely on the thickness of the salt and the buried depth of the cavity. At some sites, the cavity becomes unreasonable, and the overlying strata above the cavity collapse unfortunately. In the USA, four well-documented collapses that resulted from solution mining are Cargill sink (Kansas), Grand Saline sink (Texas), Grosse Ile (Michigan), and Tully Valley (New York) (Johnson 2005, 2008). In France, surface subsidence above salt caverns were reported at Cerville–Buissoncourt (Karimi-Jafari et al. 2008; Contrucci et al. 2011), the SG4-5 collapse at Gellenoncourt (Buffet 1998) and the LR51 collapse at La Rape (Jeanneau 2005). In Italy, catastrophic sinkholes, with serious environmental consequences, occurred in the 1980s during salt mining in Calabria (Iovine and Parise 2008), and more recently in Piedmont (Vigna et al. 2010). Similar situations have been also registered in other European countries, as at Tuzla, Bosnia Herzegovina (Mancini

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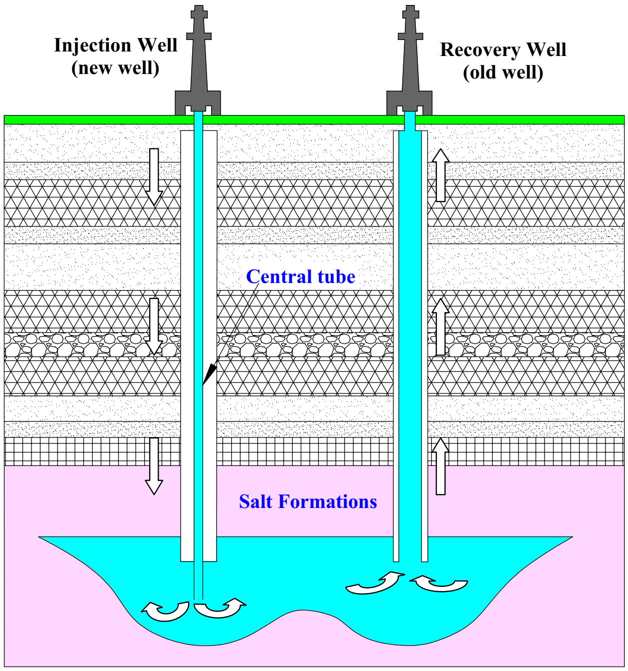

Fig. 1 Solution mining with double-well convection

et al. 2009), and in Romania (Mesescu 2011). Surface collapse hazards induced by solution mining have happened in many places of China, such as Dongxing (Anhui) (Qiu 2011), Huichang (Jiangxi) (Long and Lin 2011), Yingcheng (Hubei) (Yu 1998a, b), and Xinli (Hunan) (Fan and Li 2008; Li et al. 2008, 2009). In these places of China, the salt formations are mostly bedded salt formations (Li et al. 2014; Zhang et al. 2014, 2015a). The surface collapse may destroy houses, roads and other infrastructures, and pollute the land and water, which has become one of the important factors affecting the safe mining of salt formations.

Surface collapse can develop within days and with little advance warning (Dahm et al. 2011; Gutierrez et al. 2014). For developing early-warning systems and/or remediation schemes from such information, it is important to understand the structural development of gravitational overburden collapses. An intrinsic problem is that this mostly occurs underground and so cannot be directly observed (Parise and Lollino 2011; Parise 2015). Consequently, many researchers have turned to analytical, analog and numerical collapse simulations. Analog models (Poppe et al. 2014; Ge and Jackson 1998) readily simulate such large discontinuous strains in a three-dimensionally complete way. Most analog modeling studies have explored the general structural geometry and kinematics of collapse. However, specific collapse dimensions and conditions still cannot be obtained or inferred because of the similarity of the analog models. Two analytical models (Bérest 2016) have been promoted to explain the creation of sinkholes above salt caverns: "piston" model and "hour glass" model. However, it is not accurate that the collapse rocks are treated as a whole vertical cylinder and shear failure happens along the cylinder edge in the mechanical interpretation of the "piston" model, because the overlying strata or caprock should collapse layer by layer. Numerical simulation and theoretical analysis was carried out by Li et al. (2008, 2009) and Fan and Li (2008), and the stability of the immediate roof was considered to be one of the key factors to prevent the surface collapse. The ground movement law of the roof in solution mining of rock salt was studied by Liu et al. (1999), and a probability integral prediction formula for calculating subsidence anywhere in the overburden layer was deduced. Considering the sedimentary characteristics of bedded salt formations, the collapse of overlying strata and the surface subsidence would exhibit strongly stratified characteristics (Ren 2005; Ren et al. 2007), and thus a new 3D probability integral method was developed (Ren et al. 2009). However, the probability integral method was only suitable for the slow subsidence but not suitable for surface collapse accidents.

In view that the surface subsidence and collapse are related to the roof above a salt cavern, the stability of roof has been analyzed through beam model (Bauer et al. 1998; Michael and Maurice 2002; Liu et al. 2007) and circular plate model (Jiang et al. 2005; Bekendam and Paar 2002). For example, Bauer et al. (1998) 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. Michael and Maurice (2002) 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. Based on the catastrophe theory and simply supported beam model, dynamic balance process and instability process of cavern roof were studied by Liu et al. (2007), and the influencing factor was also analyzed. The stability of single cavern roof was studied by Jiang et al. (2005) with cusp catastrophe model of large deformation circular plate with fixed supports. The necessary conditions of instability are deduced. Considering the level stress contributed under the weight of strata and geological construction, the cusp catastrophe of the connected well roof is analyzed with the cusp catastrophe model of beam model. Bekendam and Paar (2002) researched the mechanism of roof collapse by circular plate theory, listed several possible collapse modes, 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. As a matter of fact, the circular plate model is only suitable for the salt cavities by single-well convection. Moreover,