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Mechanism of collapse sinkholes induced by solution mining of salt formations and measures for prediction and prevention

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Abstract In salt mining, the salt caverns formed by solution mining may lead to collapse sinkhole disasters. Predicting and preventing this type of sinkholes is a real and urgent problem. In this paper, three collapse sinkholes at the Dongxing Salt Mine were taken as examples to investigate the collapse mechanism of overlying strata above salt caverns induced by solution mining. Geophysical exploration was firstly carried out, with results showing that the overlying strata dropped down layer by layer; the prediction measures concluded that whether the anhydrite roof is destroyed or not can be treated as a marker for the identification of a salt cavity anomaly. Then, a mechanical model for the anhydrite roof was established. According to the model, major factors that may affect the stability of the anhydrite roof were identified and qualitatively analyzed, including the pressure decrease of the brine, the strength decrease of the rock in the roof under the immersion of brine, and the increase of horizontal stress in the roof. Numerical simulation was carried out to further analyze the collapse process and the influencing factors. Some prevention technologies were drawn as follows: (1) Mining of salt formations should be prohibited within the impact scope of the weak structural zone; (2) As regards the protective layer, a certain thickness of salt formation above the salt cavity should not be mined to prevent the dissolution upward; (3) An oil pad should be adopted to reduce or even avoid the contact of brine and roof; (4) Appropriate brine pressure should be maintained to improve the stability of the salt cavity when it is abandoned. The above prediction and prevention measures are not only applicable for halite but also suitable for other minerals obtained by solution mining, such as natural soda, Glauber's salt, and others.

Keywords Collapse sinkholes · Anhydrite roof · Mechanical model · Influence factors · Prediction and prevention measures

Introduction

Solution mining is the process of extracting soluble minerals (Johnson 1998, 2005, 2008), such as salt or potash. It typically entails creating one or several large underground cavities (Shi et al. 2015) that are filled with brine. At some sites, at the end of leaching, the cavity roof reached the top of the salt formation, allowing direct contact between the brine and marl (or argillite) layers that comprise the overburden of the salt formation. These layers are prone to weathering when in contact with saturated brine. Stoping takes place, and the cavity roof rises through the overburden. Once the cavity roof reaches the surface, surface depression happens (Ege 1984), thus creating sinkholes (Waltham et al. 2005; Gutierrez et al. 2014; Poppe et al. 2014; Kaufmann 2014).

In the USA, four well-documented subsidence/collapse features have resulted from solution mining: Cargill sink (Kansas), Grand Saline sink (Texas), Grosse Ile (Michigan), and Tully Valley (New York; Johnson 2005, 2008). In France, craters above salt caverns are located at Cerville-Buissoncourt (Karimi-Jafari et al. 2008; Klein et al. 2008; Contrucci et al.

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2011), the SG4–5 collapse at Gellenoncourt (Buffet 1998), and the LR51 collapse at La Rape (Jeanneau 2005). In Italy, a catastrophic sinkhole, with serious environmental consequences, occurred in the 1980s during salt mining in Calabria (Guerricchio 1989; Gisotti 1992; Roda and Martelli 2006; Iovine and Parise 2008), and more recently another sinkhole opened in Piedmont (Vigna et al. 2010). Similar situations have been also registered in other European countries, as at Tuzla, Bosnia Herzegovina (Mancini et al. 2009), and in Romania (Mesescu 2011). In China, surface subsidence and collapse hazards induced by solution mining have happened in many places, such as Huichang (Long and Lin 2011), Xinli (Li et al. 2009), and Dongxing (Qiu 2011), as shown in Fig. 1. Surface collapse may destroy houses, roads, and other infrastructures, and pollute the land and water (Gutierrez et al. 2014), which has become one of the important factors affecting the safe mining of salt formations.

Sinkholes can develop within days and with little advanced warning (Dahm et al. 2011; Gutierrez et al. 2014). For developing early-warning systems and/or remediation schemes, 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 2012, 2015). Consequently, many researchers have attempted to conduct analog, analytical, and numerical collapse simulations (Poppe et al. 2014). Analog models for sinkhole formation (Ge and Jackson 1998; Parise and Lollino 2011; Lollino et al. 2013; Poppe et al. 2014) readily simulate such large discontinuous strains in a three-dimensional complete way. Most analog modeling studies have explored the general structural geometry and kinematics of collapse. However, specific collapse mechanisms or conditions still cannot be obtained or inferred because of the similarity of the analog models. Two analytical models (Bérest 2016) have been proposed to explain the formation of sinkholes above salt caverns: "piston" model and "hour glass" model. In a "piston" model, a rigid cylinder of rock drops into the cavern, resulting in a sinkhole initially with vertical edges,

akin to the sinkhole at Cerville-Buissoncourt (Klein et al. 2008; Contrucci et al. 2011), the SG4–5 collapse at Gellenoncourt (Buffet 1998), the LR51 collapse at La Rape (Jeanneau 2005), and the Haoud Berkaoui crater (Morisseau 2000). The contour of the piston is circular, such that the ratio between the perimeter and area is minimal. In an "hour glass", the cavern rises until the uppermost keystone bedrock at a shallow depth is breached, enabling loose materials to flow into the cavern through a relatively narrow hole at the bottom of the sinkhole, similar to the Cargill plant sinkhole (Walters 1978), the Carey salt well #19 sinkhole (Cochran et al. 2005), the Panning sinkhole (Walters 1978), and the Bayou Corne sinkhole (Bérest 2016). The above two models generalize well both the contour and shape of the sinkholes. However, it is not accurate that the collapse rocks are treated as a whole vertical cylinder and shear failure occurs along the cylinder edge in the mechanical interpretation of the "piston" model, because the overlying strata or caprock should collapse layer by layer (Ren 2005; Ren et al. 2009). Therefore, questions still remain about when and why sinkholes will happen.

In spite of the continuing efforts by many scientists, understanding the mechanism governing the surface collapse or sinkhole disasters in salt mining remains a challenge for engineers (Gutierrez et al. 2014; Parise et al. 2015). To date, it is still not possible to accurately predict the type and scale of collapse sinkhole disasters and provide a fast and effective prevention measure. In this paper, three collapse sinkholes at Dongxing Salt Mine were taken as examples to investigate the mechanism of sinkhole disasters and provide some prediction and prevention measures. Geophysical exploration was firstly carried out to draw the geological outline and collapse process of the sinkhole. Then, a mechanical model was established to qualitatively analyze the stability of the anhydrite roof, and numerical simulation was also introduced to further analyze the influence factors of the stability. Finally, corresponding prediction and prevention measures are proposed. The research will provide significant theory and technology for the safe mining and environmental protection of the salt mine.

(a) The 2005 sinkhole   (b) The 2012 sinkhole

Fig. 1 Collapse at Dongxing Salt Mine, China

Description of the Dongxing Salt Mine

Geological setting

Rich resources of rock salt and Glauber's salt are distributed in the underground of Dingyuan County, China. China Salt Dongxing Salt Chemical Co., Ltd. (CNSIC) is one of the biggest salt miners in Dingyuan, which is located at the Dingyuan-Luqiao sub-depression. The whole shape of the salt ore bodies in Dingyuan County is an irregular oval, as shown in Fig. 2. Its long axial direction strikes nearly from east to west with a length about 8500 m and a width about 2390 m. The total area reaches about 14.4 km^2.

The outcropping lithologies are mainly silt clay and sandy clay, which belongs to the Qiju Group of Late Pleistocene Series (Qp3q), with an average thickness of ~20–30 m. Below the Qp3q, is the thick Eugene Tujinshan Group (E$_2$t), with a total thickness up to 1100 m. The salt formations are within the Tujinshan Group (E$_2$t). The main lithologies of E$_2$t include red sandstone, red sandy mudstone, and gray salt formations. According to the production experience, the red sandstone and sandy mudstone belong to the semi-consolidated soft rock which is prone to weathering, especially when exposed to brine or water.

The salt formations in the basin are buried continuously at depth of ~300–600 m. The lithologies contain rock salt (NaCl), anhydrite (CaSO$_4$), Glauber's salt (Na$_2$SO$_4$·10H$_2$O), glauberite (Na$_2$SO$_4$·CaSO$_4$), etc. The total thickness is generally ~60–160 m, and the maximum thickness is up to 200 m at the center of the basin. Generally, the thickness of a single salt layer is ~1–5 m, and the thickest (at the middle of the basin) is about 10 m. The interlayers between adjacent salt layers are mainly thin mudstone or anhydrite. The general thickness of interlayers lies in the range of ~0.5–2 m with a maximum 5.42 m.

Mining methods

The mining of Dongxing Salt Mine dates from the 1980s. The earliest method was solution mining with single-well convection. Because of a low recovery rate and low production capacity, solution mining with single-well convection was replaced progressively by double-well convection. Initially, in order to connect with well #9, a new well #17 was drilled nearby to form whole solution mining with natural double-well convection in 1993. However, the connection was not successful. Finally, well #17 had to be used as a single well.

In fact, it will take a long time for two wells to be connected via only natural processes, and the connected seam is also unknown. In order to improve the connection, a new method was adopted to form solution mining with double-well convection: the new well was drilled just at the edge of the old cavity, as shown in Fig. 3. Between 1993 and 1999, three wells (#24, #33, and #34) were drilled to connect with the old ones (#3, #1, and #7, respectively). Specifically, well #24 was planned to connect with well #3, while well #33 was drilled for well #1 and well #34 for well #7.

Well group #33 and #1 Well #33 was planned to be connected with well #1. Unfortunately, no central tube was installed in the newly drilled well. Because the old well #1 did not have a central tube, regardless of which well (#33 or #1) was selected as the injection well, the fresh water injected would always remain at the top of the cavity, due to the lower density of fresh water with respect to that of brine. Once the rock salt at the top of the cavity was dissolved by the fresh water, the overlying anhydrite roof would be exposed inevitably. After extended immersion of brine, the exposed anhydrite roof would finally evolve to collapse. In practice, the newly drilled well #33 was selected as the injection well, while well #1 was treated as the recovery well. As a matter of fact, the mining scheme did not achieve the desired results. Three accidents happened from July 1999 (beginning of production) to January 2001. In the
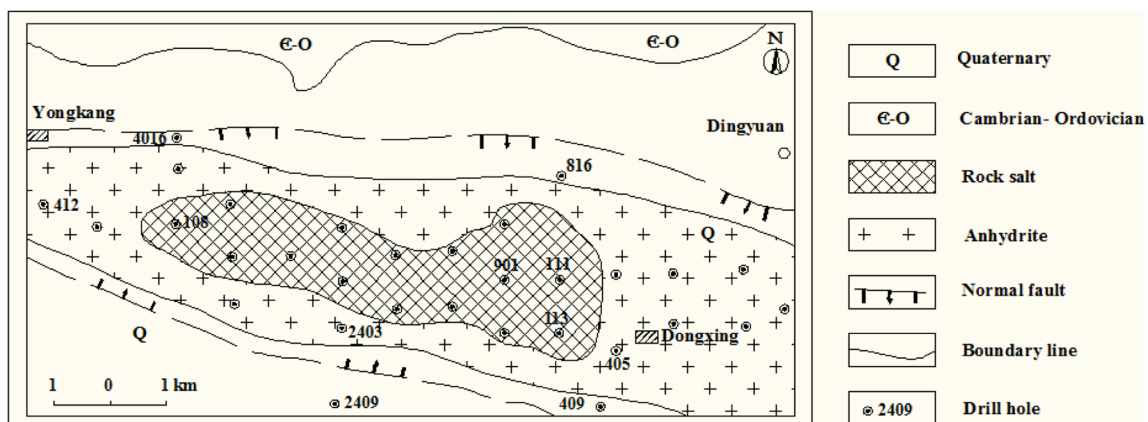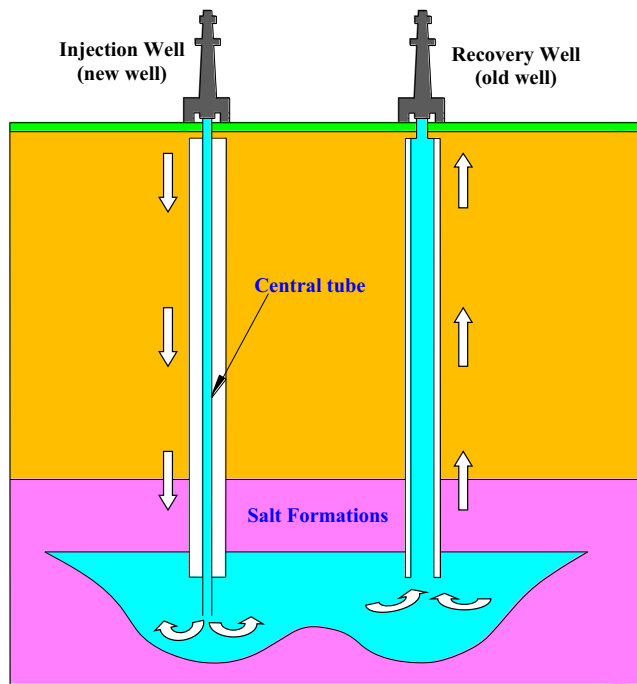

Fig. 2 Geological sketch of Dongxing Salt Mine

Fig. 3 A new adopted method to form solution mining with double-well convection

accidents, the casing was pressed flat, distorted and blocked. Finally, the two wells had to be scrapped.

Well group #24 and #3 Well #24 was drilled to be connected with well #3. According to the previous failure experience, a central tube was installed in well #24. The newly drilled well

#24 was drilled as the injection well, while well #3 was treated as the recovery well. The height of the cavity was planned to be 60 m. The cavity was designed to be buried at about −400 m. Fresh water was initially injected into the bottom of the cavity from the central tube. Due to the different density values, the injected fresh water would flow gradually upward, continuously mixing with the concentrated brine. When the fresh water arrived at the cavern roof or the recovery tube, it had been transformed into semi-saturated or saturated brine itself. Under this production mode, the formed salt cavity remained stable until 2006.

Well group #34 and #7 This well group is similar to the well group #24 and well #3. Well #34 was drilled to be connected with well #7. A central tube was installed in well #34, which was also selected as the injection well. The salt cavity is buried at about −300 m, and the height of the cavity is designed to be about 50 m. Under this production mode, the formed salt cavity remained stable until 2005.

Three collapse sinkholes and the relevant geophysical explorations

On April 10, 2012, the third collapse sinkhole happened at Dongxing Salt Mine, following the first one which occurred on December 14, 2005, and the second one that took place on March 25, 2006. Locations and dimensions of the three collapse sinkholes are shown in Fig. 4. The second collapse

Fig. 4 Locations and dimensions of the three collapses at Dongxing Salt Mine, China
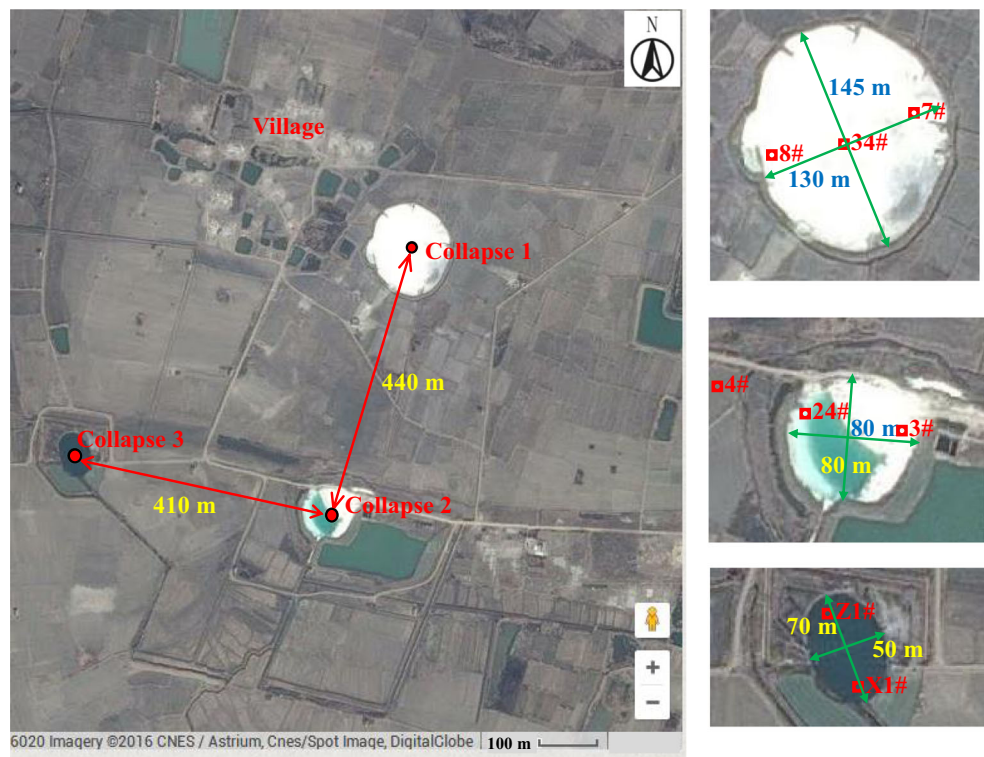
sinkhole is about 440 m south of the first one, while the third one occurred west of the second one, at a distance of 410 m. Three mining wells (#7, #34, and #8) fell into the sinkhole in the first collapse, while, respectively, two mining wells (#3 and #24 in the second one, #z1 and #×1 in the third one) fell into each of the other two sinkholes.

The first collapse sinkhole and the primary exploration achievement

On December 14, 2005, the first sinkhole occurred at 14:00. The outline of this sinkhole was approximately oval. The original collapse area was about 4000 m^2 and expanded to 8300 m^2 a week later. The deepest point of the surface subsidence reached −20 m. Initially, only wells #7 and #34 fell into the sinkhole. After a week of gradual subsidence, the adjacent well #8 also disappeared in the subsidence lake. Immediately after the first collapse, in order to provide temporary safety forecasts for the nearby villagers, geophysical explorations were carried out by the Geological Exploration Technology Institute of Anhui Province. The high-density resistivity method was firstly used to detect whether there was a cavity in the underground within −100 m throughout the whole salt mine.

In fact, due to the strong reflection of seismic waves in the anhydrite roof, it is difficult to distinguish the spatial location, size, and shape of a cavity in salt formations. Fortunately, the impedance interface between the anhydrite roof and the upper sandstone or mudstone has relatively strong energy and clearer signal, which appears to be an excellent reflection standard interface to detect the salt cavity. Therefore, the anhydrite roof can be used as a marker to judge whether this cavity is in danger or not. That is, the integrity of the anhydrite roof can be used to identify whether there could be a risk of collapse or not. Once the anhydrite roof is destroyed, the cavity may reach a larger scale, and the possibility of failures will increase. Above all, whether the anhydrite roof is destroyed or not can be treated as the anomaly identification marker of a salt cavity.

According to the above analysis, a four-dimensional seismic exploration (3D + time) was further carried out to monitor whether the cavities are abnormal or not in the entire mining area (Fig. 5). If a cavity develops continuously upward, the implemented "+" or "#" monitoring should be carried out to track its development.
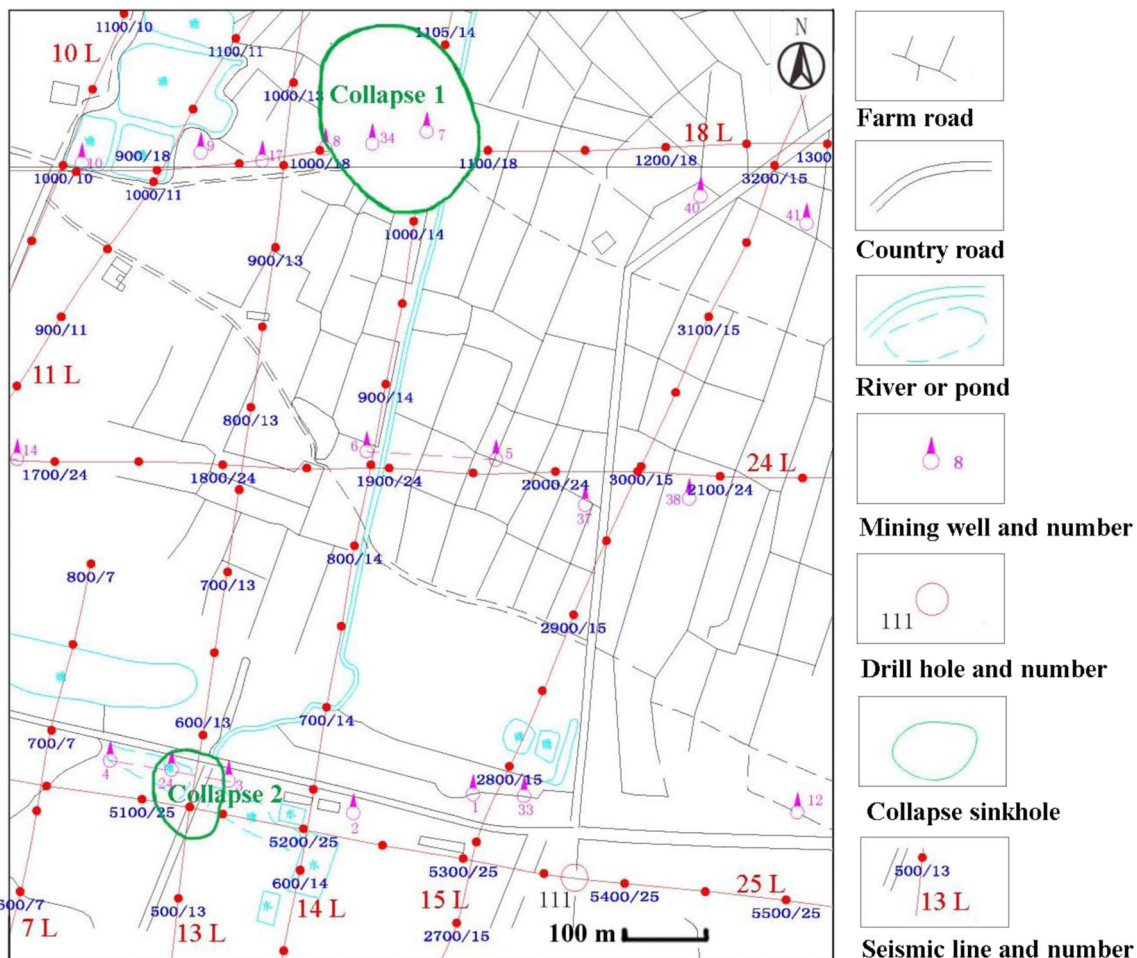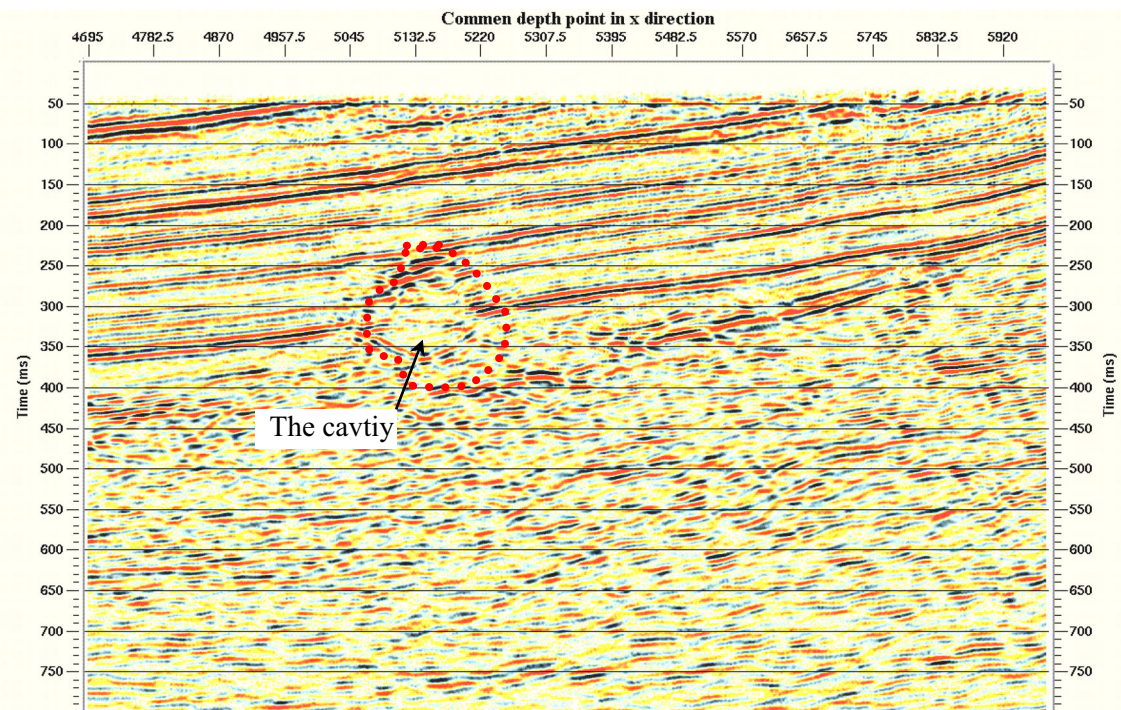

Fig. 5 Distribution of the seismic line by the four-dimensional seismic exploration

Fig. 6 Seismic exploration result of the second sinkhole (from 25 L)

Through the analysis of the seismic exploration data, an abnormal cavity (Figs. 6 and 7) was found on January 12, 2006. The cavity was located about 440 m south of the first collapse sinkhole. Then, extensive tracking and monitoring was implemented. After 73 days, the second collapse occurred at 5:20 on March 25, 2006. The mining wells #3 and #24 fell into the subsidence lake. The outline of the sinkhole was also oval, with the long axis striking from north to south. The primary collapse area was about 1500 m² and expanded to

4000 m² 3 days later. The deepest point of the surface subsidence was about −20 m.

Another abnormal cavity was found on November 2011. The cavity was located about 410 m west of the second collapse sinkhole. After 97 days of tracking and monitoring, the third collapse happened at 14:00 on April 10, 2012. The collapse outline was also oval, with the long axis extending approximately from north to south. The length of the long axis was about 58 m, while the short axis was about 38 m long. The

Fig. 7 Result interpretation of the second sinkhole
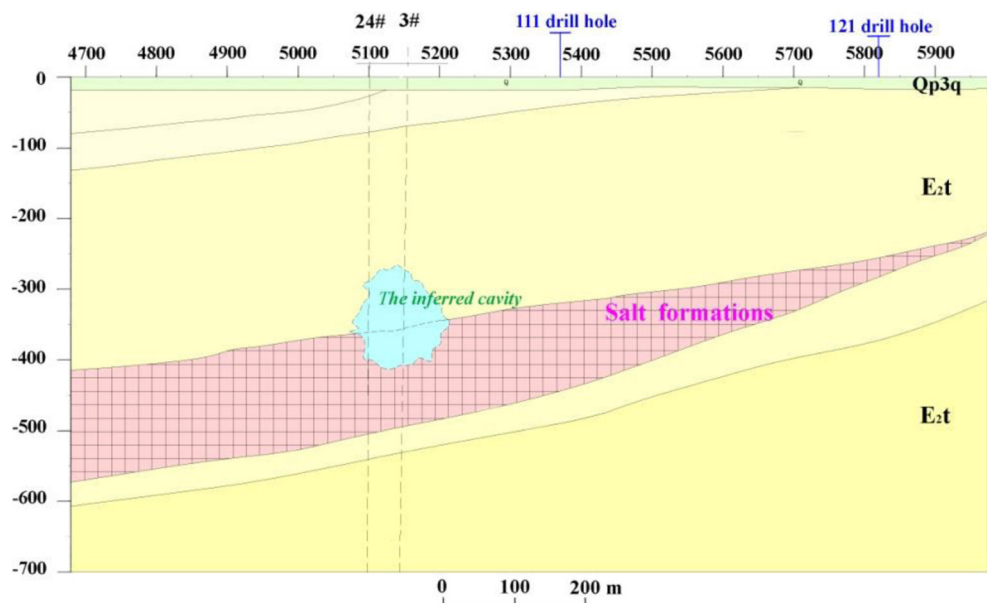
whole collapse area reached 1800 m². The deepest location was about −12 m below the ground surface.

Above all, the geophysical exploration results of the three collapse sinkholes show that whether the anhydrite roof is destroyed or not could be treated as the anomaly identification marker of a salt cavity. Therefore, the effective identification as to whether the anhydrite roof above a cavity is destroyed or not is a key indicator for accurate prediction of a collapse sinkhole.

Collapse process

The three collapse sinkholes at the Dongxing Salt Mine are hazards induced by human activities, and namely by the presence of cavities excavated by man underground (Parise 2010, 2012, 2015). The outline of the first sinkhole in the overlying strata is shown in Fig. 8. From the figure, the collapse body is almost a vertical cylinder, and the collapse wall is steep, which is in accordance with the piston model (Bérest 2016). However, the whole collapse should have happened step by step according to the geophysical exploration, namely the overlying strata should have dropped down layer by layer, as shown in Fig. 9.

Normally, when mining is stopped, fresh water is not be injected into the salt cavity. That is, the salt will be no longer dissolved, and the brine will be gradually saturated. At this situation, the cavity is stable, and the brine is sealed in the salt formations. In fact, although brine is left in the cavities and will enhance the stability of the roofs when the cavities are abandoned, so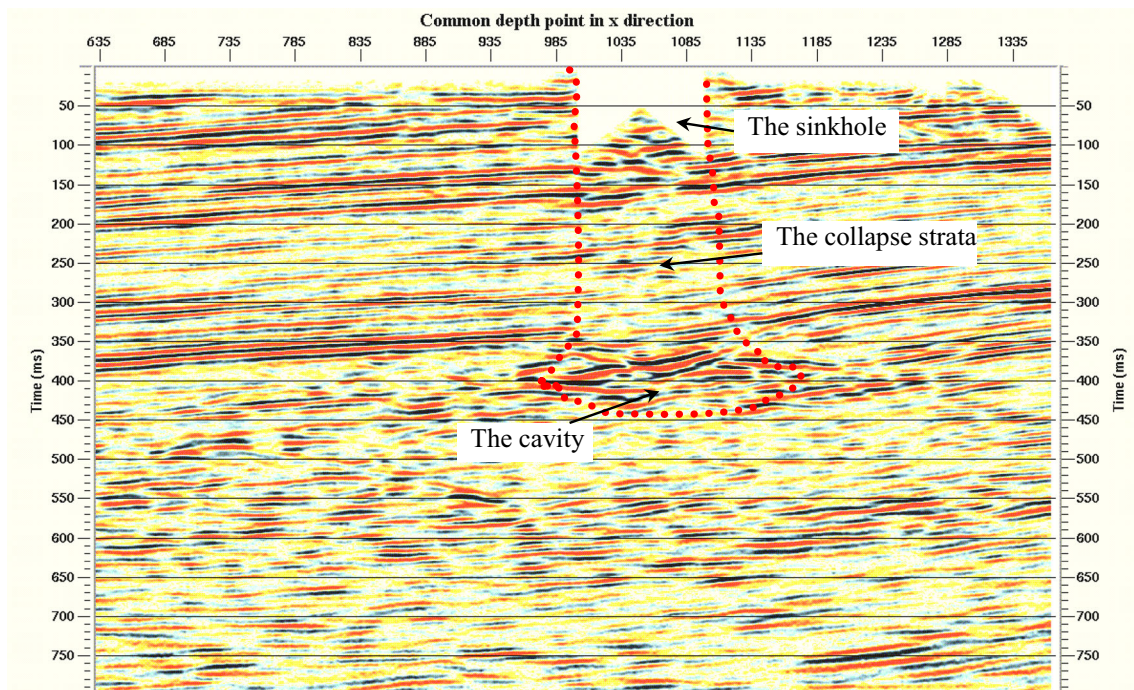me of the roofs still tend to collapse due to a variety of factors. When the anhydrite roof is destroyed, brine in the cavity will break through the anhydrite roof and dissolve the overlying strata. As such, because of the fragility and easy disintegration under the action of brine, the overlying strata above the anhydrite roof will collapse layer by layer and finally fall into the bottom of the cavity continuously. During this process, the cavity moves continuously upward until it reaches the ground surface, which means that a collapse sinkhole is formed.

The above supposed collapse pattern of the overlying strata can also be inferred from the cross-section of the Wink Sink #1 and the solution sinkholes types classified by Gutiérrez et al. (2008, 2014). However, further analysis should be carried out to identify the reasons why the anhydrite roof could break and under what conditions this will occur, especially the mechanical causes or conditions.
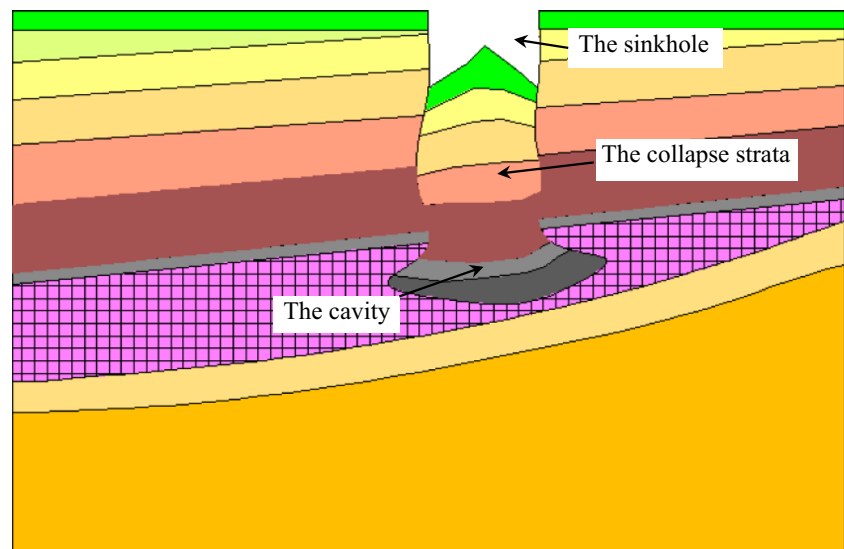
Mechanical model and influence factors

Mechanical model for the roof

In view that the collapse sinkhole is related to the cavern roof, the stability of the cavern roof should be specifically analyzed. The beam model (Bauer et al. 1998; Bekendam and Paar 2002; Jiang et al. 2005; Ren 2005; Liu et al. 2007; Parise 2008; Ren et al. 2009; Lollino et al. 2004) and plate model (Michael and Maurice 2002) are the two most widely adopted models. At the Dongxing Salt Mine, the thickness of the anhydrite roof is generally ~10–15 m. Through solution mining

Fig. 8 The outline of the first sinkhole in the overlying strata

with double-well convection, the length of a salt cavity is approximately 90–160 m, while the width is about 60–80 m. Thus, the anhydrite roof can be seen as a thin plate. As the creep of salt rocks could not be neglected, huge horizontal stress may be induced in the roof. Therefore, in the proposed model, the boundary conditions of the four edges are assumed to be flexible, as shown in Fig. 10. In the figure, l indicates the length of the roof, while b indicates the width, which can be calculated from Eq. (1) and (2):

$$l = d + 2r \tag{1}$$

$$b = 2r \tag{2}$$

where d is the well spacing, and r is the solution radius of a single well.

In the vertical direction, the roof is affected by the uniformly distributed load q, which is the difference between the vertical crustal stress q_n and the brine pressure q_w, as

shown in Eq. (3). The vertical crustal stress q_n is caused by the overlying strata and its own gravity, and the direction is perpendicular to the horizontal plane. The pressure of brine q_w is imposed on the roof, and the direction is perpendicular to the bottom surface of the roof. The uniformly distributed load q can be calculated from Eq. (3).

$$q = q_n - q_w = q_n - \gamma_b \cdot H \tag{3}$$

where γ_b indicates the unit weight of the brine, 1.2×10^3 kg/m^3, and H indicates the buried depth of the roof.

In the horizontal direction, the loads applied to the ends of the plate are defined as P, which are equal to the product of far-field in-situ stress σ_3 and the plate cross-sectional area A, as shown in Eq.(4).

$$P = \sigma_3 \cdot A \tag{4}$$

The failure process of the roof is extremely complicated. It is generally believed that the roof damage develops when the stress exceeds the tension or shear strength of the rock. According to the Mohr–Coulomb criterion, whether the tensile or shear stress exceeds the strength can be determined. If the rock in the roof suffers too large tensile or shear stresses, fractures may appear in the roof. As the height of the damaged zone increases, the fractured rock eventually falls, and the overlying strata suffer massive collapse.

Influence factors of roof failure

According to the mechanical model, the influence factors of roof stability involve the boundary conditions and the mechanical properties of the rock. From the mechanical model, three types of factors are identified: (1) the pressure decrease of the brine, (2) the increase of horizontal stress in the roof, and (3) the strength decrease of the rock.
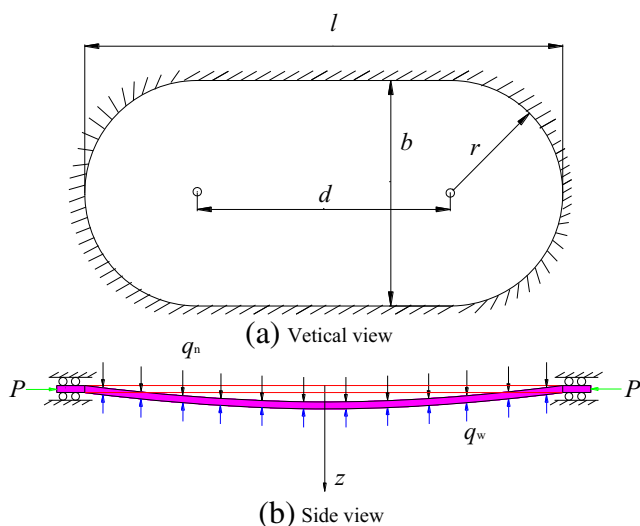
Fig. 10 Mechanical model of the anhydrite roof

Pressure decrease of the brine

According to geological investigations, concealed faults or other weak structural zones may be buried deep underground near the collapse area. If solution mining is carried out adjacent to a fault or a weak structural zone, the brine may flow out from the cavity, and the brine pressure will decrease or even vanish. Under this condition, the anhydrite roof will lack an important supporting force, which may finally lead to the destabilization and even collapse of the cavity.

Increase of horizontal stress in the roof

It is well known that salt rocks display obvious characteristics of creep and damage self-healing (Zhang et al. 2015a), whereas the overlying strata (mainly anhydrite, sandstone, and mudstone) are usually brittle and nearly incapable of damage self-healing. Because of differences in mechanical properties, differential deformation between salt rocks and the overlying strata will occur inevitably, which may result in horizontal additional stress in the roof. When the strength of the rocks cannot bear the horizontal additional stress, cracks or damage form in the rocks. Unlike salt rocks, the brittle rocks in the overlying strata are unable to self-heal. Therefore, the resulting cracks or damage in the roof are irreversible, and the gradually increasing horizontal additional stress induces failure or destruction of the roof.

Strength decrease of the rock in the roof

Soluble components, such as halite (NaCl), glauberite (Na$_2$SO$_4$·CaSO$_4$) and Glauber's salt (Na$_2$SO$_4$), are present in the anhydrite roof. Generally, the saturation brine is only saturated with halite (NaCl). As to the glauberite and Glauber's salt, they can still be dissolved in halite-saturated brine. Therefore, under the immersion of brine, the soluble components in the roof are firstly dissolved. After extended immersion in brine, the strong roof will become weaker and weaker. Finally, the overall structure of the roof will lose its integrity and inevitably lead to its collapse.

According to the above analysis, the immersion of brine will introduce a huge impact on the adjacent strata, especially on those directly above the cavity. Therefore, salt formations above a salt cavity should not be mined in engineering practice. As a protection, this layer can be used for preventing upward movement of brine. In addition, the oil pad method must be adopted, because it is especially effective to control the upward movement of brine during and after the mining process.

Numerical simulation

According to the proposed mechanical model, it is easy to qualitatively analyze the stress state of the roof, and three types of influence factors of roof stability can be identified. However, it is difficult to exactly solve the mechanical model, because it is difficult to determine the calculation parameters, such as the overburden pressure, the horizontal stress of the roof, and the mechanical parameters of the roof (including elastic modulus, Poisson's ratio, internal friction angle, tensile strength, etc.). In order to analyze the collapse process and the influence factors, numerical simulation was also carried out.

Numerical model and parameters

Numerical model

The numerical software FLAC3D (Zhang et al. 2014; Wang et al. 2015; Zhang et al. 2015a, b, 2016) was adopted. Taking the second collapse sinkhole as an example, considering the symmetry, only one fourth of the cluster is modeled to reduce the amount of computation. The complete model after meshing in FLAC3D is shown in Fig. 11. The origin of the model is located at the ground surface, corresponding to the center of the cavern layout; the horizontal plane is the x-y coordinate plane, and the vertical direction is the z axis. The height of the total model is 500 m with 0 m located at the top and −500 m at the bottom. The lower surface is fixed in the z-direction, while the four side faces are fixed in their normal directions. The three-dimensional isotropic self-weight stress field is adopted for in situ vertical stress.

Normally, a certain thickness of protective salt formations should not be mined, and the oil pad method should be also adopted. If there is not a concealed fault or a weak structural zone around, the brine will not leak, and the brine pressure applied on the roof will not drop. Under these conditions, the cavity can be kept stable according to the engineering practice. However, unfortunately, the newly designed solution mining method was carried out without an oil pad and protective salt formations. Therefore, the anhydrite roof directly suffered from brine from the beginning of operations. Under this condition, if the lower stratum falls off into the cavity, the upper stratum will be exposed to brine and be destroyed successively. Therefore, the overlying strata directly above the cavity are more vulnerable to brine than those at the lateral side. In order to realize the different performances at different locations, the overlying strata directly above the cavity are separated from the other parts, which are respectively named as anhydrite roof, mudstone roof, and clay roof in the model. Correspondingly, different parameters are adopted for the roof strata at different locations, which will be detailed in the following.

Fig. 11 Complete model after meshing in FLAC3D

Block Group
- clay
- mudstone
- anhydrite
- salt
- anhydriteroof
- mudstoneroof
- clayroof
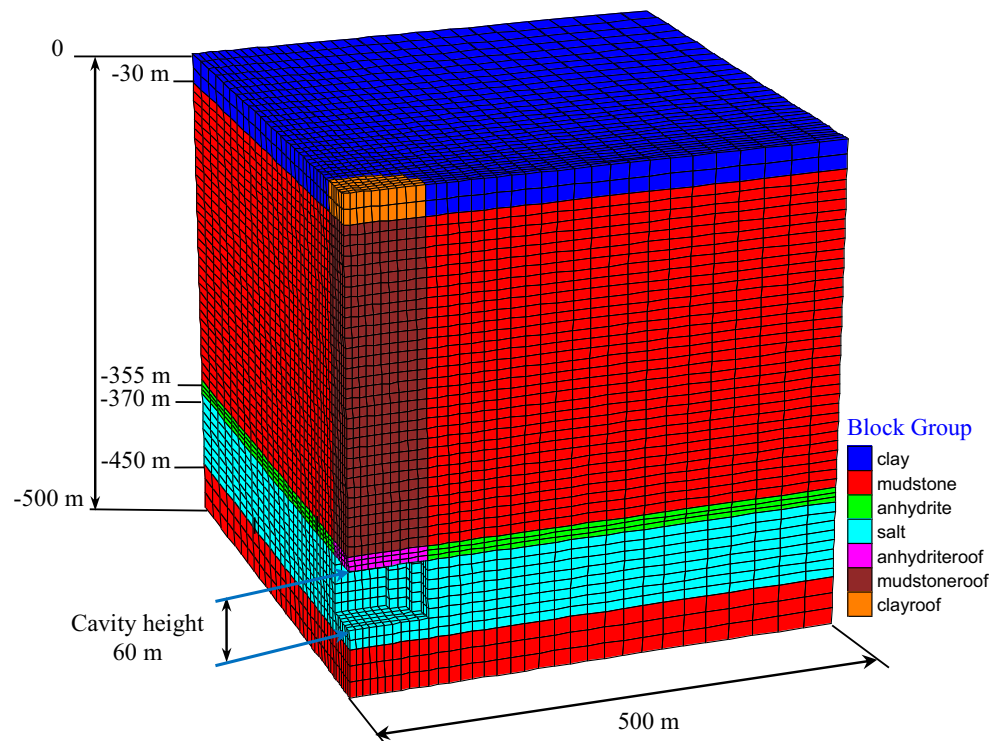
Constitutive model and calculation parameters

To study the collapse process of the overlying strata above the salt cavity, the basic parameters used in the calculations are shown in Table 1. A number of experiments (Li et al. 2014; Zhang et al. 2014, 2016) show that the mechanical parameters of rock salts are well constrained. Thus, the average values of mechanical parameters for rock salt are selected. The brine pressure in the cavity is set to the product of burial depth and density of brine, and the density of strata is 2.3 g/cm³.

The viscoplastic constitutive model Cpower (Zhang et al. 2014, 2015a, b, 2016) was adopted for salt rocks. This model combines the behavior of the viscoelastic two-component

Norton power law and the Mohr–Coulomb elasto-plastic models. The formula of the Norton power exponent creep model is written as:

$$\dot{\varepsilon}_{cr} = A\overline{\sigma}^n \tag{7}$$

$$\overline{\sigma} = \sqrt{3J_2} \tag{8}$$

where $\dot{\varepsilon}_{cr}$ indicates the steady-state creep rate; A is the material constant, 0.98×10^{-4} (MPa)$^{-n}$·a^{-1}; n is the stress exponent, 3.8; $\overline{\sigma}$ is the equivalent stress, and $\overline{\sigma} = \sigma_1 - \sigma_3$ when $\sigma_2 = \sigma_3$.

The strain-softening model (Zhang et al. 2016) was adopted for the overlying strata, which includes clay, mudstone, anhydrite, a clay roof, a mudstone roof, and an anhydrite roof. The strain-softening model is based on the *FLAC3D* Mohr–Coulomb model with non-associated shear and associated tension flow rules. In the strain-softening model, the cohesion, friction, and dilation can be defined as piecewise-linear functions of a softening parameter that measures the plastic shear strain. In this study, the cohesion, friction, dilation, and tensile strength variance are defined as functions of the plastic portion, ε_p, of the total strain. These functions are approximated in FLAC3D as sets of linear segments (Fig. 12). The strain-softening parameters for the interlayers are listed in Table 2. The yield and potential functions, plastic flow rules, and stress corrections are identical to those of the Mohr–Coulomb model.

Table 1 Basic parameters for calculation

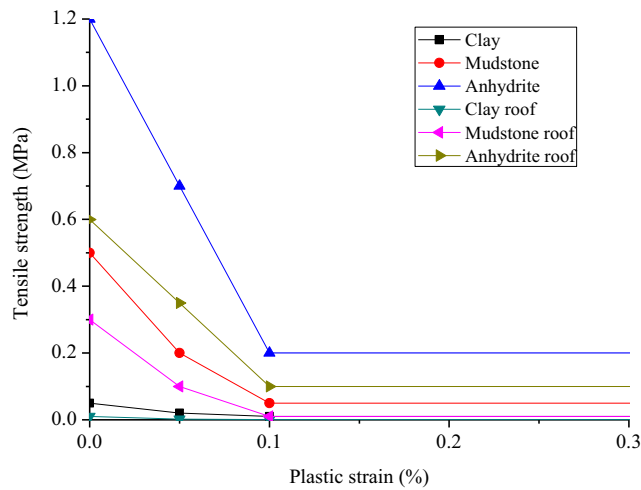| Lithology	Young's modulus E (GPa)	Poisson's ratio μ	Cohesion c (MPa)	Internal friction angle φ (°)	Tensile strength (MPa)
Clay	0.05	0.40	0.05	20	0.05
Mudstone	2	0.23	0.5	25	0.5
Anhydrite	4	0.27	1.2	27	1.2
Salt rocks	5	0.31	1.5	30	1.5
Clay roof	0.05	0.40	0.01	15	0.01
Mudstone roof	2	0.23	0.3	17	0.3
Anhydrite roof	4	0.27	0.6	20	0.6

Fig. 12 Variation of tensile strength with plastic strain

Results and discussion

Results

In order to verify the rationality of the constructed model and the adopted parameters, the simulation was firstly carried out by assuming that there is not a concealed surrounding weak structural zone and that the brine pressure is normal. Development of the plastic zones in the overlying strata is shown in Fig. 13. Initially, the plastic zones do not develop immediately to the surface but form a pressure arch in the upper strata (Fig. 13a). The pressure arch allows the rock masses to maintain a certain supporting capability for dead load. As time goes on, the pressure arch is destroyed under the immersion of brine, and the collapse region develops continuously (Fig. 13 b). After a long time of immersion, the collapse region reaches the ground surface, and a sinkhole is formed (Fig. 13c). From the figure, the plastic zones are distributed mainly at the anhydrite roof, mudstone roof, and clay roof, which are right above the cavity. The collapse body is almost a vertical cylinder. The whole collapse process revealed by the simulation is in accordance with the three occurred collapse sinkholes. It certifies that the simulation model and the inferred collapse mode are proper and reasonable.

In addition, the simulation was also carried out by assuming that there is a concealed surrounding weak zone and the brine pressure in the cavity had been reduced to zero correspondingly. Distribution of the plastic zones without brine (the pressure is zero) in the cavity is shown in Fig. 14. From the figure, a large scale of overlying strata became plastic, forming a subsidence trough in the ground surface. The plastic zones develop not only above the cavity but also laterally. A draw angle β can be figured out to separate the plastic zones from the stable zones. The draw angle β is an important parameter to depict the strata movement induced by mining, which is also related to the mechanical properties of the strata (Zhang et al. 2015b).

The subsidence trough induced by zero-pressure brine is different from the three sinkholes at the Dongxing Salt Mine. It confirms that the three sinkholes should not be caused by the extremely unfavorable brine pressure which was reduced to

Table 2 Strain-softening parameters for strata

Lithology	Parameters	Plastic strain			
		0	0.05	0.1	1
Clay	Cohesion c (MPa)	0.05	0.02	0.01	0.01
	Internal friction angle φ (degrees)	20	10	5	5
	Tensile strength σ_t (MPa)	0.05	0.02	0.01	0.01
Mudstone	Cohesion c (MPa)	0.5	0.2	0.05	0.05
	Internal friction angle φ (degrees)	25	15	10	10
	Tensile strength σ_t (MPa)	0.5	0.2	0.05	0.05
Anhydrite	Cohesion c (MPa)	1.2	0.7	0.2	0.2
	Internal friction angle φ (degrees)	27	17	10	10
	Tensile strength σ_t (MPa)	1.2	0.7	0.2	0.2
Clay roof	Cohesion c (MPa)	0.01	0.002	0.001	0.001
	Internal friction angle φ (degrees)	15	10	5	5
	Tensile strength σ_t (MPa)	0.01	0.002	0.001	0.001
Mudstone roof	Cohesion c (MPa)	0.3	0.1	0.01	0.01
	Internal friction angle φ (degrees)	17	12	7	7
	Tensile strength σ_t (MPa)	0.3	0.1	0.01	0.01
Anhydrite roof	Cohesion c (MPa)	0.6	0.35	0.1	0.1
	Internal friction angle φ (degrees)	20	15	10	10
	Tensile strength σ_t (MPa)	0.6	0.35	0.1	0.1
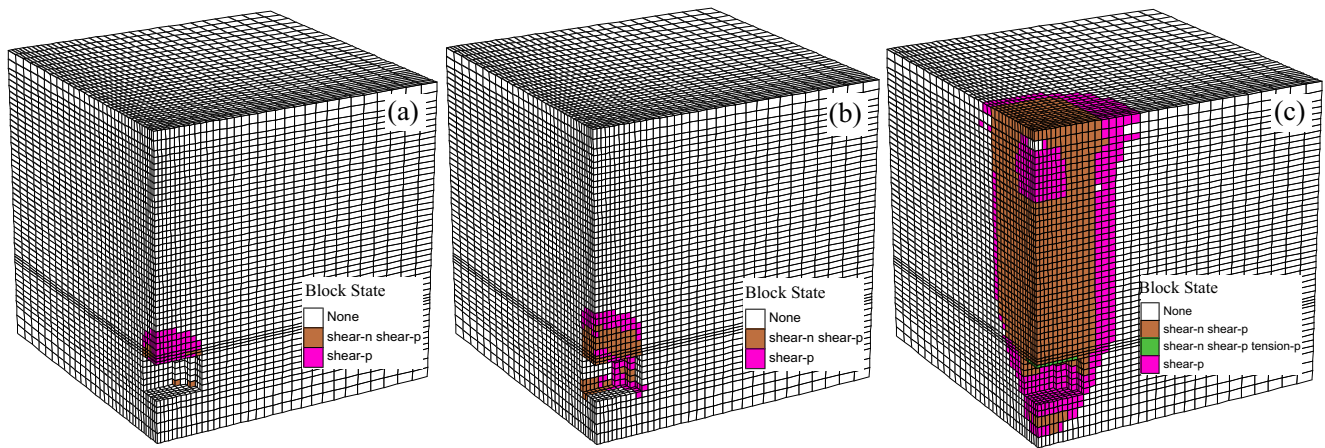
Fig. 13 Development of the plastic zones in the overlying strata

zero. As a matter of fact, the brine pressure will not decrease to zero, because the brine will not flow out completely. In fact, when the upper strata collapse, the phreatic water may penetrate into the cavity, mix with the brine, and finally add to the pressure column. This is the reason why the three sinkholes did not develop to a large-scale trough.

According to the above analysis, appropriate higher brine pressure should be maintained to improve the stability of the anhydrite roof. However, the internal pressure should not be too high, because tensile fracturing of rocks in the roof might develop at the top, as well as in other parts of the cavern (Zhang et al. 2015b), if the internal pressure is too high. Therefore, the internal pressure of the brine can be raised appropriately but not too high. Furthermore, because a large

scale of the subsidence region would be caused, the salt should not be mined within the impact scope of the weak structural zone or fault.

Discussion

The three collapse sinkholes that occurred at Dongxing Salt Mine are hazards induced by human activities in an underground environment (Parise 2015). In China, several cavities formed by solution mining are buried deep. Normally, when the mining is stopped, fresh water will not be injected into the salt cavity. In other words, the salt will be no longer dissolved, and the brine will be gradually saturated. At this condition, the brine is sealed in the salt formations and can enhance the

Fig. 14 Distribution of the plastic zones in the overlying strata when the brine pressure is set to zero
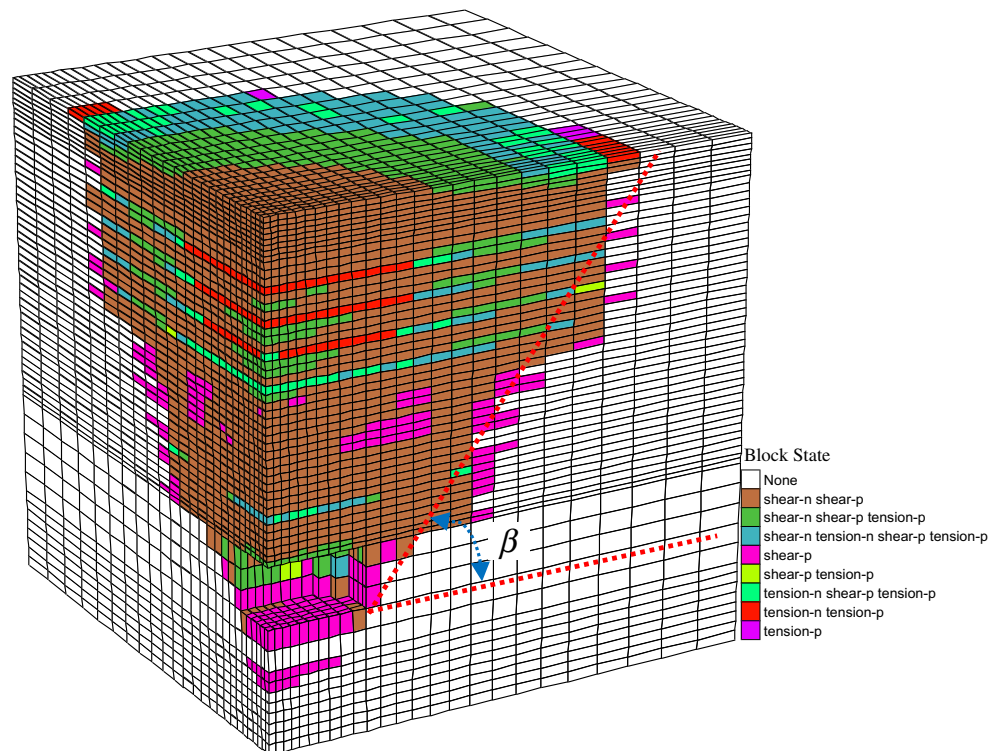
stability of the roofs. However, some of the roofs still tend to be destroyed due to various factors. When the anhydrite roof is broken, brine in the cavity will break through it and dissolve the overlying strata. From that moment on, the overlying strata will collapse and fall into the bottom of the cavity layer by layer, and correspondingly the cavity will move continuously upward. When the failure reaches the ground surface, a collapse sinkhole is formed. The collapse sinkhole may destroy infrastructures, pollute the land and water, and affect the safe mining. Therefore, a reasonable technology should be proposed to predict or prevent the occurrence of collapse sinkhole.

Prediction measures According to the results of geophysical explorations, whether the anhydrite roof is destroyed or not can be treated as the anomaly identification marker of a salt cavity. In a solution mining area, in order to provide safety forecasts for the nearby villagers, geophysical explorations should be carried out. Some prediction measures are listed as follows:

(1)　Firstly, the high-density resistivity method should be used to detect whether there is a cavity in the shallow underground of the mining area. If there is a cavity, the integrity of the anhydrite roof should be monitored by four-dimensional seismic exploration (3D + time).

(2)　Then, if the anhydrite roof is monitored, the implemented "+" or "#" monitoring should be carried out to track the cavity's development. Correspondingly, an alert must be conveyed to the nearby residents.

(3)　Finally, when the cavity develops continuously upward and the surface collapse nearly occurs, prohibition should be issued to prevent people from entering the area prone to possible collapse.

Prevention measures According to the mechanical model and numerical simulation, three types of influence factors of the roof stability were identified and further analyzed, and some prevention measures are drawn as follows:

(1)　Mining of salt formations should be prohibited within faults. If solution mining is carried out adjacent to a fault, the brine may penetrate through the intended channel to erode toward the fault zone, and then the brine pressure in the cavity will decrease, even reducing to zero. Under this condition, the anhydrite roof will lack an important supporting force, which may finally lead to large-scale subsidence.

(2)　As regards the protective layer, a certain thickness of salt formations above the salt cavity should not be mined to prevent the dissolution upward. Generally, the brine at the top of the cavity is saturated with halite (NaCl) but without the other soluble components. The soluble components in the roof may be dissolved if they are exposed to brine. A certain thickness of the salt formations on top of the cavity can be used to prevent the contact of brine and the roof.

(3)　An oil pad should also be adopted to reduce or even avoid the contact between brine and the roof. As a further step in preventing any undesirable upward solution of the salt formation, an oil pad or blanket should be introduced and maintained to float on top of the brine throughout the operation. For this purpose, the oil can be simply added in proper proportion to the solvating liquid as the latter is furnished.

(4)　Appropriate brine pressure should be kept to improve the stability of the salt cavity when it is abandoned. On one hand, because a large-scale subsidence region could be caused, the internal pressure should not be too low. On the other hand, the internal pressure should not be too high, because tensile fracturing of rocks in the roof may happen at the top, as well as in other parts of the cavity.

The above points are not only applicable for anhydrite, but also to other minerals by solution mining, such as natural soda, Glauber's salt, etc. The successful prediction and prevention technology of collapse sinkhole above a salt mine can bring huge economic benefits, besides preventing losses of life as a consequence of sinkholes.

Conclusions

In salt mining, the salt caverns formed by solution mining may lead to collapse sinkhole disasters; thus, it is an urgent technical problem to predict and prevent the overlying strata collapse and surface subsidence. In this paper, three collapse sinkholes at Dongxing Salt Mine were taken as examples to investigate the collapse mechanism of the overlying strata above salt caverns by solution mining. Geophysical exploration was firstly carried out to draw the geological outline and the collapse process of the sinkhole. Then, a mechanical model was established to qualitatively analyze the stability of the roof and the influence factors, and numerical simulation was also introduced to further analyze these influence factors. Finally, corresponding prediction and prevention measures are proposed. Some meaningful conclusions are drawn as follows:

1)　Three collapse sinkholes that occurred at Dongxing Salt Mine are hazards induced by human activities. The results of the geophysical exploration show that the overlying strata should be dropped down layer by layer, and whether the anhydrite roof is destroyed or not could be treated as the anomaly identification marker of a salt cavity. Once

the anhydrite roof fails, the cavity might reach a larger scale, and the possibility of collapse hazards will be increased. So, the effective identification as to whether the anhydrite roof has failed or not is a key technology for the accurately prediction of a sinkhole.

2) According to the proposed mechanical model for the anhydrite roof, three types of influence factors of the roof stability were identified and qualitatively analyzed, respectively, including the pressure decrease of the brine, the strength decrease of the rock under immersion of brine, and the increase of horizontal stress in the roof induced by the creep of salt rocks. Numerical simulation was then carried out to further analyze the influence of these three types of factors. According to the results of mechanical models and numerical simulation, the three factors may have significant influence on the stability of a salt cavity.

3) Some prevention measures are finally drawn as follows: (1) Mining of salt formations should be prohibited within weak structural zones; (2) As regards the protective layer, a certain thickness of salt formations above the cavity should not be mined to prevent the dissolution upward; (3) The oil pad method should also be adopted to reduce or even avoid contact between brine and the roof; (4) Appropriate brine pressure should be maintained to improve the stability of salt cavity when it is abandoned.

The above conclusions are not only applicable to halite, but also suitable for other minerals obtained by solution mining, such as natural soda, Glauber's salt, and others.

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