Petroleum 1 (2015) 82–90

Contents lists available at ScienceDirect

Petroleum

journal homepage: www.keaipublishing.com/en/journals/petlm

Original article

Stability of interbed for salt cavern gas storage in solution mining considering cusp displacement catastrophe theory

Le Yu [a, *], Jianjun Liu [b, c]

[a] School of Civil Engineering and Architecture, Southwest Petroleum University, Chengdu, 610500, China
[b] State Key Laboratory of Oil and Gas Reservoir Geology and Exploration (Southwest Petroleum University), Chengdu, 610500, China
[c] School of Geoscience and Technology, Southwest Petroleum University, Chengdu, 610500, China

ARTICLE INFO

Article history:
Received 2 February 2015
Received in revised form
7 March 2015
Accepted 10 March 2015

Keywords:
Cusp displacement catastrophe theory
The interbed
Gas storage cavern
Initial fracture drawing pace
Stability evaluation
Safety factor

ABSTRACT

Cusp displacement catastrophe theory can be introduced to propose a new method about instability failure of the interbed for gas storage cavern in bedded salt in solution mining. We can calculate initial fracture drawing pace of this interbed to obtain 2D and 3D gas storage shapes at this time. Moreover, Stability evaluation of strength reduction finite element method (FEM) based on this catastrophe theory can used to evaluate this interbed stability after initial fracture. A specific example is simulated to obtain the influence of the interbed depth, cavern internal pressure, and cavern building time on stability safety factor (SSF). The results indicate: the value of SSF will be lower with the increase of cavern building time in solution mining and the increase of interbed depth and also this value remains a rise with the increase of cavern internal pressure Especially, we can conclude that the second-fracture of the interbed may take place when this pressure is lower than 6 *MPa* or after 6 days later of the interbed after initial fracture. According to above analysis, some effective measures, namely elevating the tube up to the top of the interbed, or changing the circulation of in-and-out lines, can be introduced to avoid the negative effects when the second-fracture of the interbed may occur.

1. Introduction

Deep salt rock structure is one of the best places to storage the oil, gas and high level nuclear waste [1–3]. Compared with many salt dome reservoir conditions at overseas, the basic characteristics of rock salt deposits in China are multi-layered seams and thin thickness for the single layer, which means that there exist numerous insoluble interbeds in salt rock. Oil pad convection process for single well in solution mining can be adopted in the construction of gas storage cavern in bedded salt currently [4]. Meanwhile, the thickness of salt dome used to build the cavern at overseas is usually a bit large, and this means that it is easy to adopt oil pad process in solution mining, and then a reasonable gas storage cavern shape can be obtained. However, insoluble muddy interbeds have a huge negative impact on the process in solution mining in terms of layered rock salt deposits used to build gas storage in China. Therefore, a difficult problem, how to predict cavity shape effectively or control the interbed instability, cannot be solved currently.

Many literature about muddy interbed in salt rock mainly focus on the influence of the interbed existed on mechanical properties of salt rock and stability of gas storage cavern [5–10], but there are less literature that focus on stability of interbed in solution mining for salt cavern gas storage. The influences of insoluble interbeds on the shape of salt rock cavern were studied by Charnavel et al. [11] in France. They thought insoluble interbeds in solution mining could result in "bottleneck" in the cavity, and insoluble substances at the top of "bottleneck" would be deposited at the center of cavity bottom constantly in solution mining. Bulge would be appeared in the center of cavity bottom after solution mining, and then the brine near this site could not

---

* Corresponding author.
E-mail address: 806632369@qq.com (L. Yu).
Peer review under responsibility of Southwest Petroleum University.

Production and Hosting by Elsevier on behalf of KeAi

http://dx.doi.org/10.1016/j.petlm.2015.03.006

be discharged. This might result in the loss of effective volume for cavity. However, this study never explained mechanical model of the interbed collapse. Compared with salt rock location, salt cavern depth, cavern shape, and internal pressure, the operations of many gas storage caverns in bedded salt were investigated by Barron [12]. Considering shear and tensile failure of muddy roof, bending theory of beam could be applied to obtain the damage of this muddy roof in salt cavity by Bauer et al. [13] in America. Circular plate theory could be introduced by Bekendam et al. [14] to study mechanical theory of the roof interbed in terms of land subsidence brought by brine in salt cavity after removal, and also they listed some possible failures of the interbed such as tension failure, shear failure, crushing failure, and plastic yield. Then, roof peel, tension failure and maximum deflection were obtained by FLAC software, but this study did not explain the detailed mechanical theory for kinds of failure, and the influence of horizontal stress on roof collapse also could not be introduced in their study. Thin plate bending theory was adopted by Yang Chunhe et al. [6] to establish the mechanical model of dissolved interbeds at the top of the salt rock cavern. However, the experiment results obtained by A.A. Borisov et al. [15] in Russia had indicated: when $t/b < 1/3$ (the size of board shortest edge), this rock board model was applied in thin plate bending theory. But when $t/b > 1/3$, this model was not adopted by above theory. So there existed some limitations in terms of this interbed mechanical model.

Instability failure of the interbed for gas storage cavern in bedded salt in solution mining can be regarded as their deformation from continuous and gradual changes to system catastrophe, which is the typical nonlinear mutation problem. So cusp displacement catastrophe theory can be introduced in this paper to propose the new theoretical calculation methods and numerical models towards instability failure of the interbed. Meanwhile, underground cavity inner-tube may be bent or broke because the insoluble interbed still appears to collapse suddenly after initial fracture. Therefore, stability evaluation of the interbed after initial fracture can be established by the combination of displacement cusp catastrophe theory and stability evaluation law about strength reduction FEM, and then the SSF can be obtained. This evaluation method can improve calculation accuracy about the SSF of the interbed because the instability failure criterion cannot be obtained quantitatively by using strength reduction FEM merely. Eventually, based on this method, a specific example can be introduced to obtain the influence of the interbed depth, cavern internal pressure, and cavern building time on the stability criterion of the interbed after initial fracture.

2. Unstable fracture analysis of interbed based on cusp displacement catastrophe theory

2.1. The catastrophe theory applied in unstable fracture of the interbed

Surrounding rock system in underground engineering is a complex nonlinear system, and a unified theory towards surrounding rock stability criterion cannot be formed so far. Currently, some common rock failure criterions are applied in underground engineering, such as Drucker-Prager, Mohr-Coulomb. These criterions are based on the yield limit of rock materials, which are called yield criterion as well. We should distinguish two different rock materials deformation: yield and failure. Specifically, yield of rock materials is the demarcation point of elastic and plastic deformation, and materials change into the plastic deformation stage when these materials are up to the limit point of elastic deformation and even continue to load stress. So this point is called yield limit. Failure of rock materials is that rock deformation has been up to limit and fracture has happened while loads do not continue to increase. From the stress-strain figure of rock uniaxial compression, we can conclude that this is quite different deformation process in terms of yield and failure. Yield is the upper limit value of rock elastic deformation. Although load exceeds yield limit point, rock materials do not appear failure. This means that there exist plastic deformation between yield and failure and eventually this plastic flow can result in rock failure, namely the limit state of plastic deformation. Structural failure in geotechnical engineering is the asymptotic process that will develop and are closing in rock failure, but its failure result is sudden and instantaneous. Catastrophe Theory included singularity theory, topology, structural stability would be emerged since the 1970s to determine the exact location and time of structural instability in geotechnical engineering. This theory can describe a continuous process that is why certain features or parameters will be from one to another state suddenly. This can explain characteristic mutations in various processes and events, such as bridges broken, cracked rock, cell division, market disruption and upheaval in social structures. Cusp displacement catastrophe model in this theory can be introduced in geotechnical engineering to evaluate and determine geotechnical stability and failure node.

2.2. Unstable fracture model of interbed introduced by cusp displacement catastrophe theory

Unstable fracture of insoluble interbed in solution mining mainly means energy transition occurred in this interbed based on Catastrophe Theory, which means that displacement catastrophe happened on insoluble interbed must appear in this process. Therefore, instability of interbed in salt rock cavern is not only a displacement catastrophe happened on this insoluble interbed but also rock mass yield and fracture insoluble happened on it.

The center point O is shown in Fig. 4 and this site is regarded as the state variable of system instability collapse because the maximum displacement is appeared in this site. Vertical displacement of middle point O every dissolved process is obtained along with dissolved iteration number increased by using cusp displacement catastrophe model to analyze interbed instability. There exist the relationship between increase of cavity radius r and cavity building time t, so vertical displacement rate at point O in this model is shown as follows [16]:

$$f_o(\delta, r) = \frac{\Delta\delta}{\Delta r} \tag{1}$$

Where, δ is vertical displacement rate at point O, r is the radius of cavity, which is a dimensionless.

So Taylor series included vertical displacement rate $f_o(\delta,r)$ at middle point that is fitted by vertical displacement δ at this place every dissolved process with vertical displacement δ can be obtained and quartic polynomial equation can be selected as follows [17]:

$$f_o(\delta, r) = a_0 + a_1\delta + a_2\delta^2 + a_3\delta^3 + a_4\delta^4 \tag{2}$$

Where a_0, a_1, a_2, a_3, a_4 are all parameters.

When $q = \frac{a_3}{4a_4}$, it is as follows:

$$V = C_4P^4 + C_2P^2 + C_1P + C_0 \tag{3}$$

$$\begin{bmatrix} C_0 \\ C_1 \\ C_2 \\ C_4 \end{bmatrix} = \begin{bmatrix} q^4 & -q^3 & q^2 & -q & 1 \\ -4q^3 & 3q^2 & -2q & 1 & 0 \\ 6q^2 & -3q & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{4}$$

The equation (4) can be turned into

$$\mathrm{K} = P^4 + uP^2 + vP + C \tag{5}$$

When $C = \frac{C_0}{C_4} = (a_0 - a_1 q + a_2 q^2 - a_3 q^3 + a_3 q^3)/a_4$, and this can be seen as the shear term, because this has not contribute to equation (6) of Δ, which means that displacement catastrophe cannot be influence of it. Standard unfolding of cusp catastrophe A_3 can be described by Equation (6), and some parameters are as follows:

$$\begin{cases} K = \dfrac{V}{C_4} \\ u = \dfrac{C_2}{C_4} = \dfrac{a_2}{a_4} - \dfrac{3a_3}{8a_4^2} \\ v = \dfrac{a_1}{a_4} - \dfrac{a_2 a_3}{2a_4^2} + \dfrac{a_3^3}{8a_4^3} \end{cases} \tag{6}$$

The steady-state model of interbed can be described by Equation (6), and discriminant of this can be solved as follows:

$$\Delta = 8u^3 + 27v^2 = 0 \tag{7}$$

Critical points determined by Equation (7) are equilibrium surface, which is included by upper, middle, lower lobe of figure in space (r, u, v), and also the upper and lower ones remain steady state and the middle one is unsteady (Fig. 1).

The phase point (x, u, v) still changes at the upper lobe (or the lower one) whatever u, v can be followed. Catastrophe point set (singular point set) is concluded by vertical tangent points in equilibrium surface when it have been reached at the edge of lobe, which means that this must jump on the middle lobe.

There exist two criterions about stability of the interbed for salt rock gas storage based on catastrophe theory as follows:

(1) The interbed remains steady state when $\Delta > 0$, because displacement values are located outside the bifurcation set.

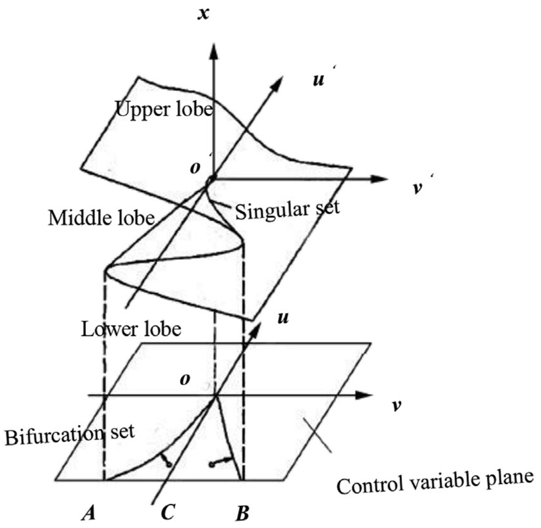


Fig. 1. Equilibrium surface and bifurcation set of cusp catastrophe model [16].

(2) The interbed has collapsed in solution mining when $\Delta < 0$, because displacement values are located inside the bifurcation set. This means that displacement values will be over the bifurcation region and this means that it has been catastrophe.

Therefore, this can be regarded as the criterions of insoluble interbeds after initial fracture and the cavity radius can be obtained in solution mining at this time.

3. Numerical example

3.1. Calculation parameters

In order to verify the proposed model, specific gas storage cavern in bedded salt is simulated as an example. The target salt rock formation where the salt cavern gas storage locates is with depth arranging from about 1000 to 1140 *m*, and the interbed is located in the underground about 1050 *m*. Its average thickness is nearly140 m. The dip angle of salt rock formation along the horizontal direction is almost 0. The section dimension and 3D shape of the salt cavern gas storage can be introduced by literature [18]. In order to satisfy the sealing requirements, the thicknesses of salt above and below salt cavern are no less than 10 m respectively. Therefore, the whole height of the proposed salt cavern is controlled at less than 120 *m*. Physical and mechanical property parameters of salt rock [19] obtained by experiments are shown in Table 1.

Cavern mesh model is shown in Fig. 2. Insoluble interbed mainly consists of mudstone, and salt rock is located above and under this interbed. Saline solution can be found in the cavity under the interbed. A quarter of this overall model can be selected because this model is axisymmetric body. This can improve the computing speed. Due to the dimensions of salt cavern are much smaller than the depth of strata, parts of overlying strata are simplified as an equivalent overburden pressure subjected to the upper boundary to improve the calculation efficiency. The equivalent overburden pressure is about 16 *MPa* calculated by the parameters from Table 1. Six times of the salt cavern maximum diameter can be seen as the distances between the boundaries and salt cavern center to eliminate the boundary effects. According to the field geological data, the maximum, minimum horizontal and vertical in situ stresses are 29.6 *MPa*, 20.6 *MPa*, and 27.4 *MPa* below ground at 1000 *m* respectively. The following boundary conditions are applied: the bottom has zero displacement boundary; all outer sides have horizontal zero displacement boundaries in the vertical direction.

The commercial software *ABAQUS* can be adopted in whole calculation. During this process, creep behavior in the salt rock and insoluble interbed can be ignored primarily because the operation time of cavity boundary expansion in solution mining is quite brief in comparison to the time of this creep. All rock layers are regarded as the isotropic, homogeneous and continuous material, and also Mohr-Coulomb plastic model can be applied in constitutive model of these rock layers.

3.2. Initial fracture drawing pace of the interbed unsupported in the cavern based on cusp displacement catastrophe model

According to actual injection situation and the progress of cavity solution [20], the diameter of this cavern has increased in solution mining. We can obtain the expansion value of this cavern diameter (0.3 *m*), and system water displacement value is 100 m^3/h. liquid pressure loaded bottom board of the insoluble

Table 1
Geological parameters of the salt carven region.

Formation type	Density (kg/m^3)	Young's Modulus (GPa)	Poisson ratio	Cohesion (MPa)	Friction angle (degree)	Tensile strength (MPa)	Uniaxial compressive limit strength (MPa)
Mudstone	2800	10	0.27	1.0	35	1	/
Mudstone interbed	2800	4	0.27	1.0	35	1	/
Rock salt	2200	18	0.3	1.0	45	1	14.72

interbed and the wall of cavity, and vertical pressure loaded liquid medium in the gas storage cavern can be ignored.

Numerical simulations can be divided to three steps:

(1) Rock stress can be obtained on the basis of known boundary condition and mechanical property of rock material.
(2) Displacement parameters at the first step should be returned to zero, and then the excavation of salt rock in the cavern can be obtained by the method of birth-death element.
(3) Vertical displacement characteristic value Δ at the middle point O (as shown in Fig. 3) of this interbed is regarded as the catastrophe criterion. So the radius of cavity happened catastrophe can be obtained and then caving pace of insoluble interbed (L) can be calculated as well.

Fig. 4 presents relation between cavern radius and displacement mutation of interbed. From this, we can conclude the displacement of interbed changes gradually with the increase of “excavation” time when the radius is lower than 2.7 *m*. However, this displacement has to take place catastrophe when this displacement reaches to 2.7 *m*. This means that the interbed have happened failure while this radius is up to 2.7 *m*, namely 9 days in solution mining. At this time, cantilever length of the interbed is initial fracture pace when this interbed has taken place collapse.

3.3. Section dimension and 3D shape of the salt cavern gas storage with the interbed after the initial fracture based on catastrophe theory

According to the results in section 3.2, cantilever length of interbed has reached to 2.7 m after 9 days later in solution mining when this interbed taken place initial fracture as shown in Fig. 5.

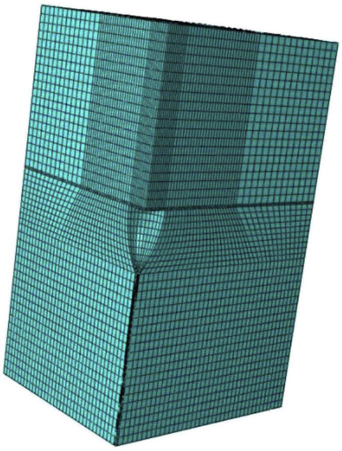


Fig. 2. Cavern mesh model.

4. Stability evaluation of interbed after the initial fracture based on cusp displacement catastrophe model

Underground cavity inner-tube may be bent or broke because the insoluble interbed still appears to collapse suddenly after initial fracture. This has a huge negative influence on the construction scheme in solution mining. Therefore, a quantitative evaluation method towards the prediction of interbed stability should be introduced in this area. Instability failure of the interbed for gas storage cavern in bedded salt in solution mining can be regarded as their deformation from continuous and gradual changes to system mutation, which is the typical nonlinear mutation problem. Therefore, stability evaluation of the interbed after initial fracture can be established by the combination of displacement cusp catastrophe theory as well and stability evaluation law about strength reduction of finite element method, and then the SSF can be obtained. This evaluation method proposed in this paper can improve calculation accuracy about SF of the interbed because the instability failure criterion cannot be obtained quantitatively by using the finite element strength reduction merely.

4.1. Strength reduction finite element method (FEM) based on cusp displacement catastrophe model

Theory of Strength reduction FEM is that the new values of c', φ' can be obtained by strength parameters of rock material (c, φ) divided by reduction factor F, And then this new rock material parameter can be regarded as the calculation parameter, namely trial calculation constantly. Strength parameters of rock material should be reduced constantly until this rock is up to critical failure status [21,22].

Strength reduction equation is as follows:

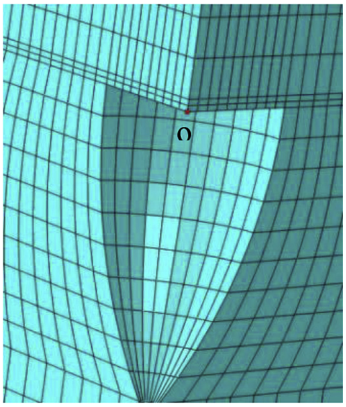


Fig. 3. The middle point O of interbed.

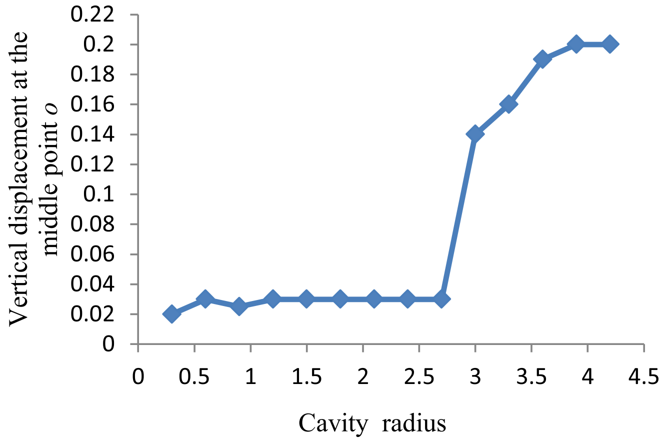


Fig. 4. Relation between cavern radius and displacement mutation of interbed.

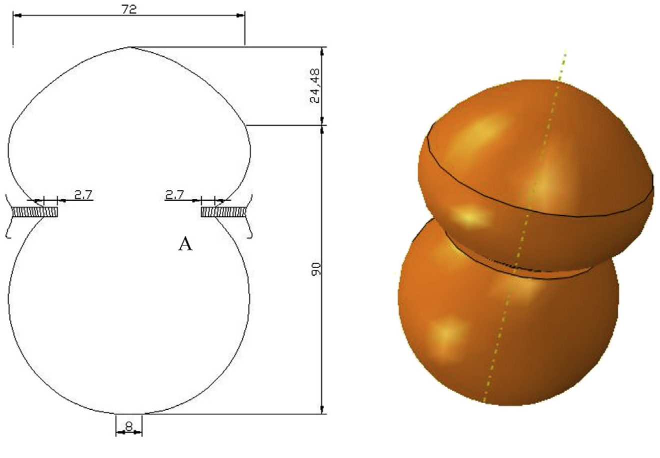
$$C' = \frac{C}{F} \tag{8}$$

$$\varphi' = \arctan\left(\frac{\tan\varphi}{F}\right) \tag{9}$$

Strength reduction FEM can be introduced in the failure analysis of interbed after initial fracture in gas storage cavern. The SF of interbed can be obtained by reducing its strength parameters constantly until this rock is up to critical failure status [23,24]. This SSF of interbed is the ratio between the strength of factual rocks mass on the failure surface and the strength when this failure happened.

Some smaller values should be selected in initial value of strength reduction factor, such as 1.02, which means that it can be guaranteed higher failure strength of salt rock. Also, this can be ensured that the stress and strain of this interbed remain field engineering situation that is influenced by initial boundary and loads.

The value of stress in the interbed is up to salt rock failure strength after reduction by increasing the reduction factor. Once this failure appears in this rock slightly, the increase of strength reduction factor may result in the large scale failure in this interbed and then load capacity will disappear in it. Strength reduction FEM can be adopted to simulate the instability failure of interbed, but this method may result in premature plastic expansion or larger scale deformation prematurely primarily because this can be influenced by stress concentration at salt rock junction and irregularity of interbed. If we adopt this value as the failure discrimination point of interbed, this method can result in the results conservatively, which means that this cannot reflect safety in reality. Instability failure of the interbed in gas storage cavern can be regarded as the process of displacement catastrophe and yield fracture. Therefore, Strength reduction FEM can be introduced to analyze the instability problem of interbed. In this process, functional relationship δ (F) between vertical displacement δ and strength reduction factor F can be obtained, and then cusp displacement catastrophe model can be introduced to evaluate the stability of interbed after initial fracture quantitatively.



(a) (b)

Fig. 5. Section dimension and 3D shape of the salt cavern gas storage with the interbed after the initial fracture (unit: m).

Vertical displacement δ at end point A of cantilever interbed (as shown in Fig. 5) can be obtained by reduction of its strength under the multi-level strength conditions. And then Taylor series about vertical displacement δ and the curve of strength reduction factor F can be fitted by this displacement δ at point A under every strength condition, then selecting quartic polynomial equation can be obtained as follows:

$$\delta(F) = a_0 + a_1F + a_2F^2 + a_3F^3 + a_4F^4 \tag{10}$$

Where a_0, a_1, a_2, a_3, a_4 are all parameters.

The stability of interbed can be obtained by the cusp displacement catastrophe model in section 2.2 based on equations (6) and (7).

4.2. *The strength reduction of interbed stability after initial fracture based on cusp displacement catastrophe model*

Shear and tensile failure are considered to be the main failure of interbed. Mohr-Coulomb criterion in *ABAQUS* software can be used to calculate primarily because both shear and tensile failure can all applied in this criterion. Meanwhile, the large scale deformation failure in the rock can be achieved by the large scale deformation in *ABAQUS* as well. Strength reduction of interbed stability after initial fracture based on cusp displacement catastrophe model is assumed as follows: (1) the interbed rock is one relatively complete material; (2) Mohr-Coulomb strength criterion and the assumption of the large deformation can be used in this material.

Shear failure criterion in Mohr-Coulomb as follows:

$$f_s = \sigma_1 - \sigma_3 N_\varphi + 2c\sqrt{N_\varphi} = 0 \tag{11}$$

Where $N_\varphi = \frac{1+sin\varphi}{1-sin\varphi}$, σ_1 is the first principal stress, *MPa*; σ_3 is the third principal stress, *MPa*; φ is rock mass friction angle; c is cohesion.

Tensile failure criterion is:

$$f_t = \sigma_3 - \sigma_t = 0 \tag{12}$$

Where σ_t is tensile strength and the maximum is lower than $C/\tan\varphi$, *MPa*.

The strength reduction of interbed stability after initial fracture based on cusp displacement catastrophe model is as follows [25]:

(1) The shape of gas storage cavern in bedded salt rock, its mechanical parameters and boundary condition can be established. Also, the numerical model can be obtained.

(2) Rock cohesion c and internal friction angle φ can be obtained by initial strength parameters of rock mass, and then plastic finite element method can be used until convergence.

(3) Rock cohesion c and internal friction angle φ used by Mohr-Coulomb model should be reduced many times by increasing the reduction factor F_i. So rock strength parameters C_i', φ_i' after completing the ith reduction is as follows:

$$C_i' = \frac{C}{F_i} \tag{13}$$

$$\varphi_i' = \mathrm{arc}\left(\frac{\tan\varphi}{F_i}\right) \tag{14}$$

Where F_i is the ith reduction factor.

(4) Vertical displacement δ at middle point of this interbed corresponded with different reduction factor F_i can be obtained and then the relationship between displacement δ and reduction factor F_i can be fitted into quartic polynomial equation.

(5) These parameters can be applied in the calculation of cusp displacement catastrophe model (8), and then variable values u and v in singular point set corresponded with vertical displacement of interbed can be obtained. At last, based on the equation of cusp displacement catastrophe model, we can determine whether this interbed in gas storage cavern remain stability.

This repeats above steps until $\Delta < 0$. This means that reduction factor before can be seen as the SSF of interbed in gas storage cavern.

4.3. *Stability influencing factors of interbed after initial fracture*

In order to verify the stability evaluation method of interbed after initial fracture, we can still use the model in section 3.1, and then stability safety factor of interbed after initial fracture and its influencing factors can be analyzed. In this section, we discuss some important influencing factors such as interbed depth, cavern internal pressure, and cavern building time.

Taking different depth of interbed as an example, strength reduction FEM based on cusp displacement catastrophe model can be introduced to solve the SSF of interbed. In order to obtain the influence of the interbed depth on its stability, its depth in this paper select 1020, 1050, 1080, 1100 *m*, respectively and the inner pressure is 16 *MPa*. The maximum vertical displacement corresponded with different reduction factor at end point A of cantilever interbed can be obtained by the increasing of strength reduction factor constantly and then quartic polynomial equation between different depth of vertical displacement and reduction factor can be calculated by regression method. Fig. 6 presents that the maximum vertical displacement of interbed nearly remains a constant with the change of reduction factor when this factor also remains a lower value. However, catastrophe phenomena will occur once this exceeds the critical value, which means that the value of displacement increases a lot obviously.

Taking the interbed located underground 1050 *m* as an example, this can illustrate that strength reduction FEM based on cusp displacement catastrophe model can be introduced to solve the SSF of interbed. The vertical displacement of cantilever interbed at end point A can be selected as the study object.

Fig. 7 presents that the vertical displacement of interbed at middle point A increases gradually with the rise of reduction factor. The displacement rises slowly when F_i remains lower value ($F_i < 1.88$), whereas the plastic flow has happened in plenty of interbed calculation unit when $F_i \geq 1.88$. Therefore, we can select $F_i = 1.87$, and then based on equation (3), vertical displacement δ and reduction factor F_i can be fitted into quartic polynomial equation while $F_i \leq 1.87$ as follows:

$$\delta = 1.6321F_i^4 - 9.0495F_i^3 + 18.474F_i^2 - 16.392F_i + 5.5279 \tag{15}$$

The parameters in the fitting curve of vertical displacement δ and reduction factor F_i can be applied in equation (6) and equation (7) of catastrophe model, and this can calculate $u = -0.17$, $v = 0.14$, so $\Delta = 0.49 > 0$.

Similarity, we can also select $F_i = 1.88$, and then based on equation (3), vertical displacement δ and reduction factor F_i can be fitted into quartic polynomial equation while $F_i \leq 1.88$ as follows:

$$\delta = 4.9303F_i^4 - 27.285F_i^3 + 55.727F_i^2 - 49.696Fi + 16.519 \tag{16}$$

The parameters in the fitting curve of vertical displacement δ and reduction factor F_i can be applied in equation (6) and equation (7) of catastrophe model, and this can calculate $u = -0.34$, $v = 0.003$, so $\Delta = -0.31 < 0$.

Based on above analysis, when the depth of interbed is 1050 *m*, the SF of interbed after initial fracture remain between 1.87 and 1.88, and 1.87 can be seen as more safety value.

If the SSF of interbed should improve to calculate more precisely, dichotomy can be used in this process, such as $F = 1.875$. We repeat above process, and if $\Delta > 0$, this means that the SSF of interbed after initial fracture remains [1.875, 1.88]. But if $\Delta < 0$, this means that the SSF of interbed after initial fracture remains [1.87, 1.875]. Therefore, the scope of this SSF can be scaled down from above process, and then the simulation precision can be improved by this method. This cannot complete in traditional strength reduction FEM.

Fig. 8 presents relation between the number of plastic elements of interbed and reduction factor when the interbed is located underground 1050 *m*. This indicates that the number of plastic zone of interbed fluctuates with the rise of reduction factor, the whole remain the non-linear rise with the increase of reduction factor. The number of plastic zone of interbed appears to be catastrophe and then remain a constant while $F_i > 1.88$. This means that the entire interbed unit remains plastic state. This may result shear failure, which indicates that the interbed has been damaged.

When the depth of interbed is 1020, 1050, 1080, 1100 m, respectively, relations between the value of Δ and reduction factor F_i as shown in Fig. 8. In this figure, this value of Δ fluctuates quickly at critical stable safety factor, which means that instability failure of the interbed after can be regarded as their deformation from continuous and gradual changes to system catastrophe. So this also concurs with theoretical study in this paper, which means that this method proposed to analyze the stability problem of interbed is reasonable and practical Fig. 9.

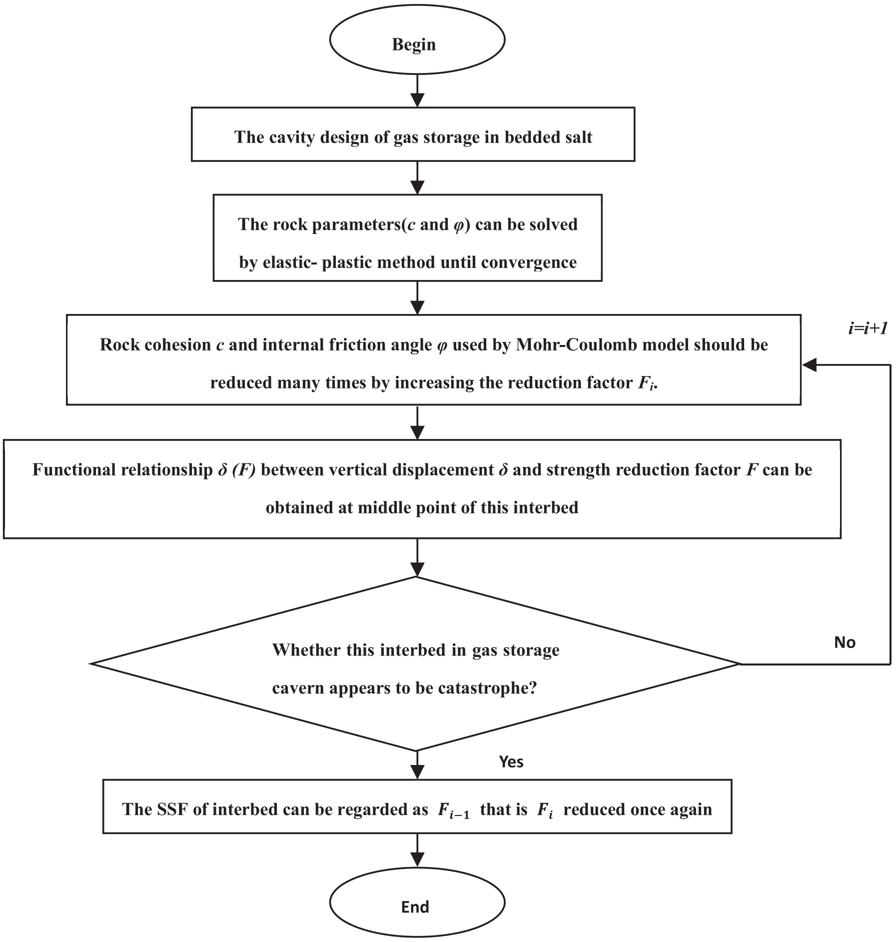


Fig. 6. Program flow diagram.

Similarity, taking the interbed located underground 1050 *m* as an example, relation between cavern internal pressure, cavern building time and safety factor as shown in Figs. 10 and 11.

Fig. 10 presents stability safety factor of the interbed after initial fracture increases with the rise of cavern internal pressure, because the rise of this pressure can have contribute to the decrease of deviatoric stress. Meanwhile , when cavern internal pressure is lower than 6 *MPa*, the stability safety factor is lower than 1.0, which means that this interbed appears to be catastrophe and even second-fracture happens in it. This has a huge negative influence on the construction scheme in solution mining. Fig. 11 presents the stability safety factor of interbed after initial fracture decreases a lot constantly. Second-fracture happens on this interbed after 6 days when it has been initial fracture. This may result in the change of cavity shape and it has a huge negative to control its shape.

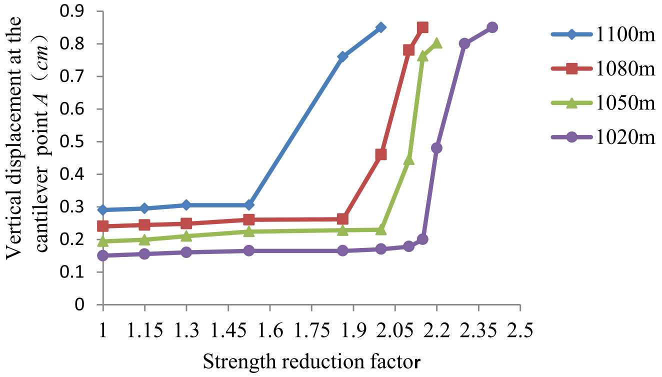


Fig. 7. Relations between the max. vertical displacement and reduction factor of point A when there exist different values of interbed deposit location.

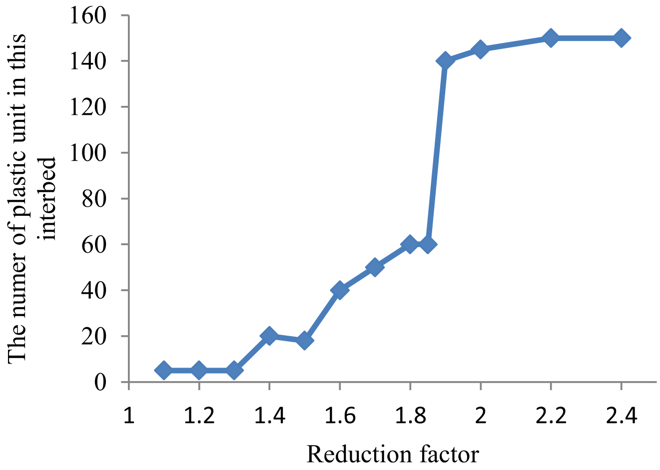


Fig. 8. Relation between the number of plastic elements of interbed and reduction factor.

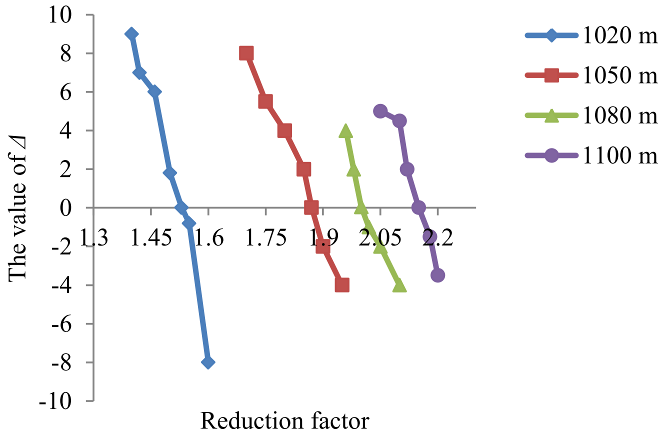


Fig. 9. Relations between the value of Δ and reduction factor F_i when there exist different values of interbed deposit location.

5. Application future

Based on above numerical example, we can conclude that this new stability method about interbed for salt cavern gas storage in solution mining can be used to evaluate or predict the interbed instability.

Firstly, displacement cusp catastrophe theory can be introduced in this paper to propose the new theoretical calculation methods and numerical models towards instability failure of the interbed. Based on this new method, we can obtain 2D and 3D pictures in solution mining and control the shape of gas storage cavern during this period by initial fracture drawing pace of the interbed. This has a great beneficial on predict the shape of gas storage in practical designing.

Moreover, stability evaluation of the interbed after initial fracture can be established by the combination of displacement cusp catastrophe theory and stability evaluation law about strength reduction of FEM. This evaluation method proposed in this paper can improve calculation accuracy about SSF of the interbed because the instability failure criterion cannot be obtained quantitatively by using strength reduction FEM merely. This method has good generality, which means that it can be used in practical geotechnical engineering to evaluate its stability. For example, the SSF of the interbed after initial fracture remains a rise with the increase of cavity pressure can obtained by a specific engineering simulation in this paper. Especially, the value of SSF will be lower than 1 and this means that the interbed may be taken place the instability failure and even happened the second-fracture when the cavity pressure is lower than 6 *MPa*. The SSF of the interbed happened initial fracture will be lower with the increase of time in cavern building time. Especially, the second-fracture of the interbed may take place when the SSF will be lower than 1 after 6 days later of the interbed after initial fracture. According to above analysis, some effective measures, namely elevating the tube up to the top of the interbed, or changing the circulation of in-and-out lines, can be introduced to avoid the negative effects when the second-fracture of the interbed may occur.

Overall, this new stability method has a great beneficial on the evaluation and predication of interbed for salt cavern gas storage in solution mining in terms of application future.

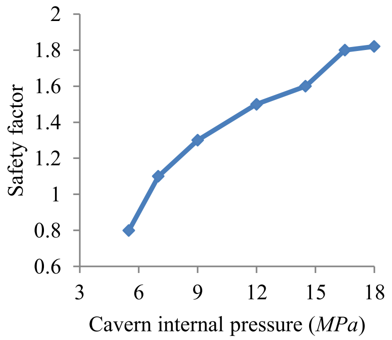


Fig. 10. Relation between cavern internal pressure and safety factor.

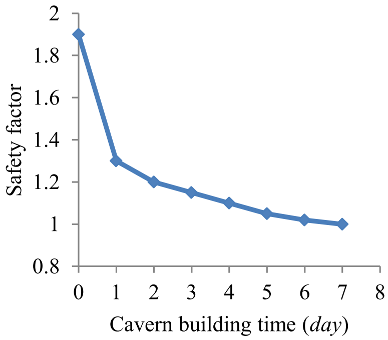


Fig. 11. Relation between cavern building time and safety factor.

References

[1] R.L. Thoms, R. M Gehle, A brief history of salt cavern use, in: The 8th World Salt Symposium, [S. l.], vol. 2, Elsevier, 2002, pp. 207–214.
[2] J.J. Liu, X.B. Yu, J.Z. Zhao, Numerical simulation of geostress and pore pressure evolution around oil or water well under different injection-production ratio, Math. Probl. Eng. (2013), http://dx.doi.org/10.1155/2013/604748.
[3] C.H. Yang, W.G. Liang, H.D. Wei, Investigation on possibility of energy storage in salt rock in China, Chin. J. Rock Mech. Eng. 24 (24) (2005) 4409–4417.
[4] Q.M. Wang, Salt Deposits in Solution Mining, Chemical Industry Press, Beijing, 2003.
[5] Y.P. Li, C.H. Yang, et al., Experimental research on deformation and failure characteristics of laminated salt rock, in: Proceedings of the 6th Conference on the Mechanical Behaviors of Salt, Taylor & Francis Group, London, 2007.
[6] X.L. Shi, Y.P. Li, C.H. Yang, Research on mechanical mechanism of interlayer collapse in solution mining for salt cavern gas storage, Rock Soil Mech. 30 (12) (2009) 3616–3626.
[7] X.L. Shi, Y.P. Li, C.H. Yang, Test study of influence of brine on tensile strength of muddy intercalation, Chin. J. Rock Mech. Eng. 29 (11) (2009) 2302–2308.
[8] C.H. Yang, Y.P. Li, X.Y. Yin, Cosserat medium constitutive model for laminated salt rock and numerical analysis of cavern stability in deep bedded salt rock formations, in: Proceedings of 41st U.S.Rock Mechanics Symposium & 50th Anniversary, Curran Associates Inc, Golden, USA, 2006.
[9] J.J. Liu, L.Z. Zhang, J.Z. Zhao, Numerical simulation on open wellbore shrinkage and casing equivalent stress in bedded salt rock stratum, Sci. World J. (2013), 1155/2013/718196.
[10] Y.P. Li, J. Liu, C.H. Yang, Influence of mudstone interlayer on deformation and failure characteristics of salt rock, Chin. J. Rock Mech. Eng. 25 (12) (2006) 2461–2466.
[11] Charnavel Yvan, Lubin Nicolas, Insoluble deposit in salt cavern – test case, in: SMRI Fall Meeting. [S. l.]: [s. n.], 2002.
[12] T.F. Barron, Regulatory, technical pressures prompt more U.S. salt – cavern gas storage (OGJ special), Oil Gas J (1994) 55–67.
[13] S.J. Bauer, B. L Ehgartner, B. L Levin, et al., Waste disposal in horizontal solution mined caverns- considerations of site location, cavern stability, and development considerations, in: SMRI Fall Meeting. [S. l.]: [s. n.], 1998.
[14] R.R. F Bekendam, W. A Paar, Induction of subsidence by brine removal, in: SMRI Fall Meeting. [S. l.]: [s. n.], 2002.
[15] P. evans James, Permeability of fault-related rocks and implication for hydraulic structure of fault zones, J. Struct. Geol. 119 (11) (1998) 1393–1404.
[16] H.B. Gao, W.G. Liang, The Study on Influencing Factor of Gypsum Rock Interlayer for the Building Cavern in Bedded Salt Rock Deposit, 2013.
[17] Y.N. Zhao, Q.H. Wu, et al., Strength reduction method to study stability of goaf overlapping roof based on catastrophe theory, Chin. J. Rock Mech. Eng. 29 (7) (2010) 1425–1434.

[18] P. Qu, R.C. Shen, H.C. Xu, Design method for geometry of dissolution cavity of salt gas storage considering the stability, Act A Pet. Sin. 28 (6) (2007) 142–146.

[19] W.Z. Chen, G.J. Wu, Y.H. Dai, C.H. Yang, Stability analysis of abandoned salt caverns used for underground gas storage, Chin. J. Rock Mech. Eng. 25 (4) (2006) 849–854.

[20] Ozarslan Ahmet, Large-scale hydrogen energy storage in salt caverns, Int. J. Hydrogen Energy 37 (2012) 14265–14277.

[21] M.T. Luan, Y.J. Wu, T.K. Nian, Slope instability criterion and its application of plastic zone in strength reduction finite element method, J. Disaster Prev. Mitig. Eng. 23 (3) (2003) pp.1–pp.8.

[22] S.Y. Zhao, Y.R. Zhen, W.D. Deng, Stability analysis on jointed rock slope by strength reduction FEM, Chin. J. Rock Mech. Eng. 22 (2) (2003) pp.254–pp.260.

[23] Y.L. Zhao, Y. Zhang, W. Wan, Bedded salt rock mechanical properties and creep failure model, Mineral Eng. Res. 25 (1) (2010) pp.16–pp.20.

[24] H. Zheng, C.G. Li, C.F. Li, Finite element method for solving the factor of safety, Chin. J. Geotechnical Eng. 24 (5) (2002) pp.626–pp.628.

[25] Y.R. Zheng, C.Y. Qiu, H. Zhang, Exploration of stability analysis methods for surrounding rocks of soil tunnel, Chin. J. Rock Mech. Eng. 27 (10) (2008) 1968–1980.