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Research on the Stability and Treatments of Natural Gas Storage Caverns With Different Shapes in Bedded Salt Rocks

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ABSTRACT Because of complex geo-conditions, many caverns by solution mining in bedded salt rocks have different irregular shapes. To verify the feasibility of using irregular-shaped caverns for underground gas storage (UGS), four typical cavern-shapes are selected, and the stability of each type is evaluated and compared by using the numerical simulation methods. The simulation results show that the UGS salt cavern with irregular wall shape has the lowest volume shrinkage and displacement of the wall rock, but larger plastic zones appear in their overhanging and concave parts. Ellipsoid-shape cavern has the best stability. Cylinder-shape cavern and cuboid-shape cavern have the poorest stability. In these two types of caverns, large deformations occur in the roof and sidewall, which pose a great potential of inducing collapse in the wall rock. By comparison of the stability characteristics in different positions of the wall rock, we found that the roof shape has a much greater influence than the sidewall on the stability of a cavern. The roof must be designed as an arch to improve cavern stability. Treatments to improve the stability of irregularly shaped caverns by changing operational pressure and utilization way or by modifying the caverns' shape are also discussed. So, this study not only determined the stability state of different shaped caverns for gas storage in bedded salt rocks, but also provides the ways to modify the irregular-shaped caverns for storage applications.

INDEX TERMS Natural gas storage, bedded salt rock, cavern roof, cavern stability analysis, modifying cavern shape.

I. INTRODUCTION

To face up to the global environmental problems [1]–[3], as the greatest carbon-emission country [4], China has paid great efforts to promote and use clean energies [5]–[7]. Taking the clean energy-natural gas of China for an example [8], [9], the related exploration, exploitation, and storage have been significantly developed [10]–[13]. Especially for the construction of natural gas storage facilities, the investment by the country is continuous to increase [14]. From 2000 to the present, China has planned and constructed 25 underground gas storage (UGS) bases, accounting for a total gas storage volume of about 100×10^8 m^3. These UGS facilities have made great contributions to ensure the liability of the gas supply in winter as well as control the haze problem.

The UGS facilities are predominantly constructed in depleted gas reservoirs, mainly in North China and along the Bohai rim. But in the large central, eastern and southern regions of China, there are almost no UGS facilities [15], [16]. In recent years, along with the increasing consumption of natural gas in these regions, the UGS facilities needed for gas peaking shaving and emergency supplies have increased significantly. In these regions, the geo-conditions are characterized by broken tectonics, and they lack suitable depleted gas reservoirs or brine aquifers for UGS construction. Fortunately, these regions have a large number of salt rocks, which may provide the option for UGS construction, too [17]–[21]. Salt rock has extremely low permeability, small porosity, self-healing and water-solution properties [22]–[26]. In addition,

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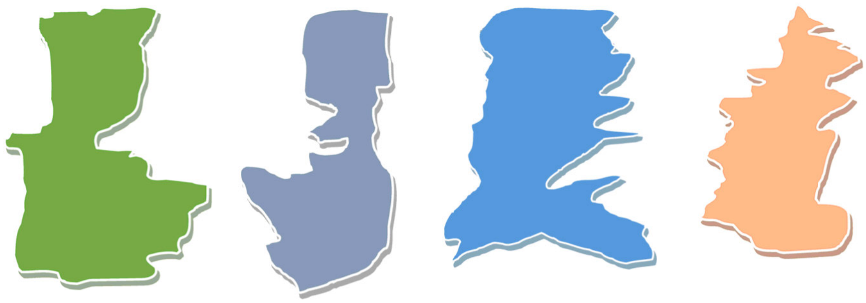

FIGURE 1. Irregular shapes of salt caverns abroad and domestically [44], [45]: (a) BM-5, USA, (b) Kraak-101, Germany, (c) JT86, China, (d) JT-2, China.

salt rock is a typical soft rock mass and can sustain large deformation without failure, the deformation characteristics of which are much different from brittle rocks, such as sandstone [27], [28]. Therefore, caverns in salt rocks leached by water solution are widely used for energy media storage as well as for chemical waste disposal. Globally, UGS in salt rocks is one of the three main storage methods for UGS [29]. The UGS salt caverns are characterized by high safety, fast switching between injection and withdrawal, high turnover frequency, and low amount of cushion gas [30]. So, they are regarded as the best option of a UGS facility that can face up the complex gas market. In the EU region, the working gas volume supplied by salt caverns occupies over 15 % of the total [31]. As early as 2008, the UGS salt caverns have provided 23 % of the UGS sites in the USA [32]. Therefore, constructing UGS in salt rocks is also a reasonable and acceptable option in China.

In recent years, China planned 5 bases of UGS facilities in salt rocks, including Jintan, Huai'an, Pingdingshan, Qianjiang, and Yingcheng [33]. When all the UGS salt caverns are completed, it will increase the working gas volume by about 80×10^8 m^3. Then these UGS salt caverns will play a significant role in the natural gas peak shaving in central, eastern and south regions of China. In addition, along with the growing gas storage requirement of the local gas companies and local governments, the local construction of UGS salt caverns will be gradually put on the agenda, such as the UGS in Heze salt mine, Shandong, the UGS in Ningjin salt mine, Henan, and the UGS in Anning salt mine, Yunnan. A peak of UGS salt cavern construction will appear in the following one or two decades in China.

However, different from the salt domes abroad, most of the salt rocks in China have a bedded structure. The bedded salt rocks contain numerous non-salt interlayers, consist of thin salt layers and have a low grade of halite [34]–[37]. These conditions greatly increase the difficulty and cost of cavern construction in bedded salt rocks. In previous studies, the UGS salt caverns in bedded salt rocks are usually designed as regular shapes, such as an egg shape, an ellipsoid shape, or a pear shape. Then evaluations of the cavern stability for long-term storage are conducted using these regular-shaped caverns [38]–[42]. But usually, by the current solution mining methods, it is usually difficult to construct caverns with regular shapes due to the heterogeneity and complexity of the bedded salt rocks. Li et al stated that about 60 % of the caverns in Jintan salt mine have unexpected or irregular shapes [43]. If an underground excavation has an irregular shape, stress concentrations and large deformations may appear in the wall rock, which will greatly increase the failure risk. In addition, the investment of cavern construction is rather large, for instance, constructing one 2×10^5 m^3 salt cavern costs about ¥8×10^7 yuan and takes as long as 4-5 years. Yet, the requirement for the national gas storage space is urgent. So, the problem is, how is the stability of the irregular caverns, and can they be used or not?

In fact, no matter whether in salt domes or in bedded salt rocks, many caverns have non-ideal shapes. Although researchers have proposed a lot of shape designs for salt caverns for energy storage [18], in reality, many caverns that are actually used have irregular shapes [44], [45]. FIGURE 1 shows four typical irregular cavern shapes that have been used for energy storage both domestically and abroad. FIGURE 1(a) and FIGURE 1(b) show salt caverns used for energy storage in the USA and in Germany, which have been used for many years. It follows that irregular-shaped caverns still have good stability for energy storage once reasonable operation plans are adopted. In addition, there are also some stability accidents that occurred in irregularly shaped salt caverns in civil and abroad [46]–[48], such as roof failure or sidewall rock collapse. FIGURE 1(c) and FIGURE 1(d) show domestic irregular caverns in bedded salt rocks that are previously designed and constructed for gas storage. Their stability and feasibility for UGS will be evaluated in this study. Once they have acceptable stability for gas storage, many such caverns can be used for gas storage and save a large amount of construction investment.

In conclusion, it is found that there are two types of non-ideal or irregular caverns. One is the caverns that have a plane roof rather than an arch roof. The other is the cavern that has irregular sidewalls that may contain overhanging blocks or concave protrusions. Obviously, due to the presence of non-salt interlayers, the degree of irregularity of the caverns

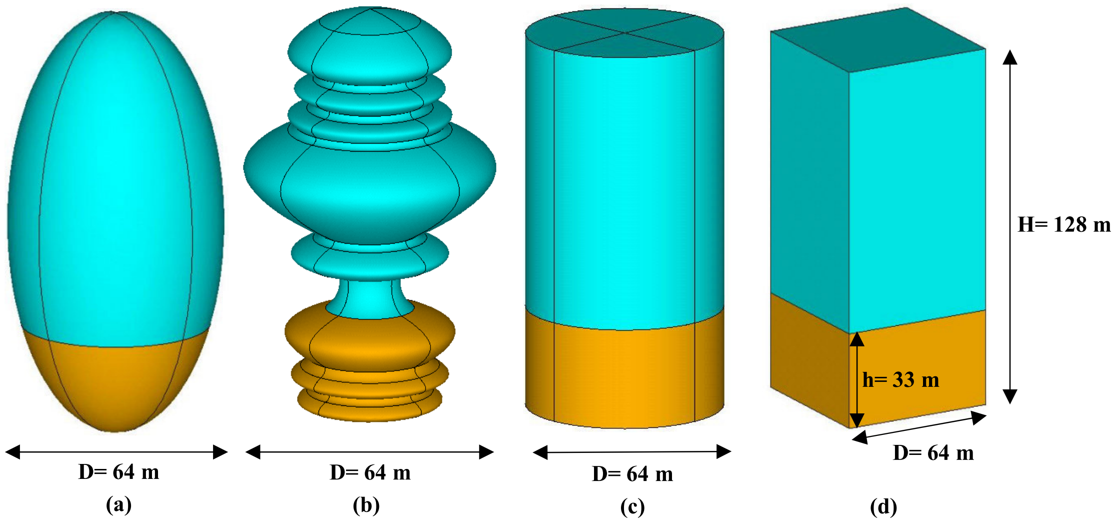

FIGURE 2. Four different shapes of salt caverns: (a) ellipsoid-shape, (b) irregular-shape, (c) cylinder-shape, and (d) cuboid-shape cavern (Blue-part stands for the effective volume of the cavern, yellow-part stands for the sediments in the bottom of the cavern).

in bedded salt rocks is more significant. Although irregular caverns are successful for energy storage in salt domes, the physical and mechanical properties of the bedded salt rocks are much different from those of the salt domes. Therefore, the stability evaluations of the irregular-shaped UGS salt caverns in bedded salt rock still require special investigation and determination. In this way, reliable references can be provided for the gas storage in these caverns.

In this study, one potential UGS site, Huai'an salt mine, is selected as the demonstration base. Four typical cavern shapes of the cavern are selected for the long-term stability evaluation of these caverns for UGS. Typical indexes are chosen for the stability evaluation of these caverns. The difference in the stability characteristics of the four types of cavern are analyzed, and the key issues that impact the stability of the cavern are identified, and useful suggestions are put forward. In the end, discussions are given on the operational plans, application ways and potential modifications for the irregular-shaped caverns. This study provides references to assess the stability of the irregular-shaped caverns in bedded salt rocks. It also proposes methods for the optimization of cavern application, and repairing or modifying cavern shape.

II. CAVERN SHAPES AND SIMULATION MODEL

A. SELECTION OF CAVERN SHAPES

As FIGURE 2 shows, four typical shapes of the cavern are selected for stability analysis and comparison. The ratio of height to diameter of all the four caverns sustain to be 2: 1, with a height of 128 m and a maximum diameter of 64 m. Meanwhile, a sediment portion with a height of 33 m is designed at the bottom of the cavern. Above all, each cavern stands for one engineering condition stated as follows:

Shape-type 1: an ellipsoid-shape cavern. This cavern has an ellipsoid shape overall. The maximum diameter is located in the central position. The upper-part boundary is an elliptical arch. The sidewall rock is also smooth. This shape stands for the ideal cavern shape that could be designed.

Shape-type 2: an irregular-shape cavern. Interlayers may prevent the upper solution and promote the lateral solution. As a result, a necking shape (overhanging block) appears at the positions where insoluble interlayers are present, and concave protrusions appear in the thick salt layers.

Shape-type 3: a cylinder-shape cavern. This cavern has a constant circular cross-section from the bottom to top, and it has a plane roof. In bedded salt rocks, if interlayers collapsed easily, and oil-blanket is not used, then such a cavern shape may be formed.

Shape-type 4: a cuboid-shape cavern. Such a cavern shape is rarely constructed by water solution technology. But when using dry mining, such a cavern shape can be created. This cavern is just used as a comparison example in this study.

B. NUMERICAL MODEL

The demonstration site of the UGS salt caverns is in the Zhaoji block, a part of Huai'an salt mine, in the eastern-north position of the Hongze sunken block, Jiangsu Province of eastern China. The roof depth of the salt-bearing strata is within 1700-2100 m, and the cumulative salt bearing formation is over 120 m in thickness. The salt-bearing strata have mudstone and anhydrite cap rock. Many different lithotypes of non-salt interlayers are distributed in the salt-bearing formation. This salt region has stable geo-conditions, a suitable thickness of salt-bearing strata, as well as good depth, and hence is an ideal site for a UGS facility.

Based on the geological information of the Zhaoji block of Huai'an salt mine, the numerical simulation model has been established, using ANSYS software (FIGURE 3) and then imported into the FLAC^{3D} software for calculation [49].

TABLE 1. **Rock mechanical parameters.**

Rock style	Bulk modulus (GPa)	Shear modulus (GPa)	Cohesion (MPa)	Angle of internal friction (°)	Tensile strength (MPa)
Silt mudstone	9.19	4.81	2.4	31	1.3
Light gray anhydrite	10.35	5.47	2.2	35	1.4
Gray anhydrite	10.92	5.54	2.3	35.5	1.5
Gypsum mudstone	13.04	6.81	2.9	36	1.6
Rock salt	8.67	3.95	1.93	37.5	1.2
Mudstone	14.13	7.09	3.0	39	1.7

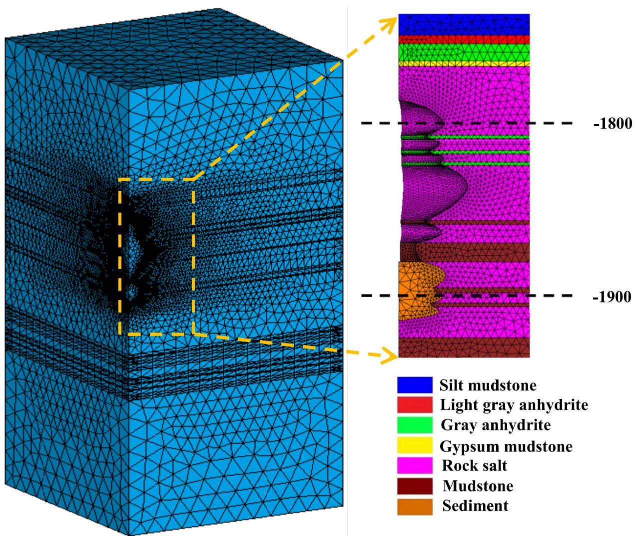

FIGURE 3. **Numerical simulation model: the entire model and rock strata around a cavern.**

The model has a size of 350 m, 350 m and 700 m in length, width and height, respectively. Due to symmetry, the model contains only 1/4 part of the cavern. The overlying strata have also been simplified to a vertical load ($\sigma_z = 35.65$ MPa) acting on the upper surface of the model. The bottom and lateral boundaries are fixed and initial stress is applied to these boundaries. Taking the model containing the irregular-shape cavern for an example, the total number of elements is 541,689, and the total number of nodal points is 95,151. Rock mechanical parameters are shown in TABLE I.

During the natural gas storage stage, the wall rock is under steady creep [50]. The following C-power steady-creep law is used:

$$\dot{\varepsilon}_t = A(\sqrt{3J_2})^n \tag{1}$$

where, $_t$ is the steady creep rate. $J_2 = (1/6)[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]$, is the second invariant of the deviatoric stress tensor. A and n are two creep parameters which are obtained by experiments, referring to our previous studies [33].

The internal gas pressure of a salt cavern is changed due to switching between gas injection and gas withdrawal. The minimum gas pressure is selected as 14 MPa from the point of view of cavern integrity. The maximum gas pressure is designed as 33 MPa which equals about 0.8 times of the vertical stress at cavern roof. The variation of the gas pressure over one year is given as:

$$P_{igp} = 23.5 + 9.5\cos(2\pi t) \tag{2}$$

where, P_{igp} is the internal gas pressure, MPa; t is the operating time of the UGS salt cavern, a (years). FIGURE 4 shows the fluctuation of gas pressure cycles.

III. SIMULATION RESULTS AND ANALYSIS

Stability evaluation of a UGS salt cavern is a systematic task. In this study, three typical indexes, volume shrinkage rate of the cavern, plastic zones of wall rock and displacement of the wall rock are selected to evaluate the stability of the UGS caverns. These three factors are usually utilized as the main criteria for the safety evaluation of UGS caverns in salt formations [33], [40], [41].

A. VOLUME SHRINKAGE RATE OF UGS CAVERN

FIGURE 5 shows that the UGS caverns with cuboid shape and cylinder shape have very large volume shrinkage rates, approaching 21% and 19%. The irregular shape cavern and ellipsoid shape cavern have much smaller volume shrinkage rates than the former two caverns. Over 30 years, their volume shrinkage rates are 6.3% and 7.5%. So, from the point of view of shape design, the latter two are much more preferable than the former two.

It is surprising that the irregular-shaped cavern has a smaller volume shrinkage rate than the ellipsoid-shaped cavern, even though the latter has a much more regular shape. Generally, if the wall rock is irregular, larger deformation and stronger stress concentrations are prone to occur, thus resulting in easier failure. However, in fact, the irregular-shaped cavern presents the minimum volume shrinkage rate. Therefore, further investigations are necessary.

B. PLASTIC ZONES: DISTRIBUTION AND VOLUME

Plastic zones are determined by the computing failure criterion built-in in the FLAC^{3D} software, which includes the Mohr-Coulomb criterion and the maximum tensile stress criterion equation (3):

$$\begin{aligned} f_s &= \sigma_3 - \sigma_1 N_\varphi + 2C\sqrt{N_\varphi} \\ f_t &= \sigma_t - \sigma_1 \end{aligned} \tag{3}$$

where, σ_1 is the maximum principal stress and σ_3 is the minimum principal stress. C is the cohesion and φ is the internal friction angle. $N\varphi = (1 + \sin\varphi)/(1 - \sin\varphi)$. σ_t is the tensile strength of the rock mass.

Rock salt and mudstone are soft rocks. Plastic states in the vicinity of the cavern should be carefully controlled or

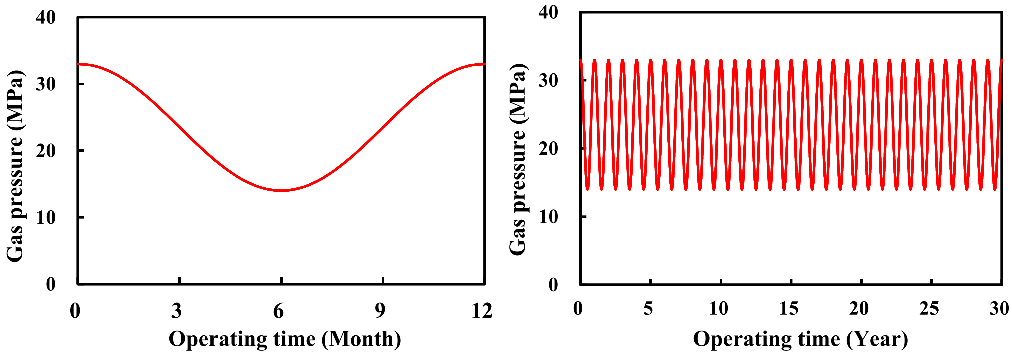

FIGURE 4. Gas pressure cycle in one year (one operating cycle) and 30 years (30 operating cycles) in a salt storage cavern.

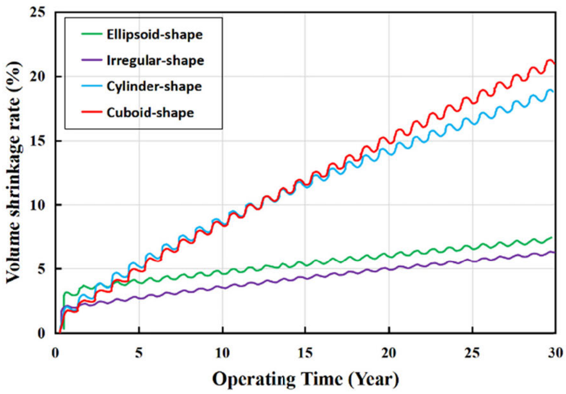

FIGURE 5. Volume shrinkage rates for UGS caverns with four different shapes.

decreased so as to constrict deformations from becoming too large. Distributions of plastic zones are significant to show the local stability-state of the wall rock. FIGURE 6 shows the distribution of plastic zones for the four different shaped caverns after 30 years for gas storage.

From FIGURE 6, the plastic zones of the ellipsoid-shape cavern are far less extensive than those of the cylinder-shaped and cuboid-shape caverns. The cylinder-shape and cuboid-shape caverns have much more extensive plastic zones in the wall rock, especially around the roof and the corner positions. This indicates that these two caverns behave poor stability when used for UGS. Although the irregular-shape cavern has a little smaller volume shrinkage than that of the ellipsoid-shape cavern, its plastic zones are more extensive than those of the ellipsoid-shape cavern. This may be because stress concentrations are more intense in the wall rock for the irregular shaped caverns, and thus more extensive plastic zones occur. This can be verified by the distribution of the plastic zones. That is, more plastic zones appear in the overhanging protrusions and concave positions. Therefore, attention should be paid to these positions for irregular cavern for UGS, especially the potential collapse of these positions.

1) VOLUME OF PLASTIC ZONES

To further clarify the characteristics of the plastic zones in the wall rock, the volume of the plastic zones of each cavern is recorded and plotted in FIGURE 7. Along with the gas pressure variation induced by gas injection and withdrawal, the fluctuation of plastic zones is also induced by the changing stress in the wall rock. As FIGURE 7 shows, both the value and the fluctuation amplitude of the plastic zones are very different from each other. Both the ellipsoid-shape cavern and the irregular-shape cavern have a much smaller volume and amplitude of the plastic zones compared with those of the cylinder-shaped cavern and cuboid-shape cavern. In addition, the irregular-shape cavern has greater plastic zones volume than that of the ellipsoid-shape cavern, although its volume shrinkage rate is a little lower than that of the latter one. Therefore, to evaluate the stability of salt cavern, besides volume shrinkage rate, other factors, such as the plastic zones and local failure of the wall rock should also be considered.

C. DISPLACEMENT IN WALL ROCK

Displacement of the wall rock is another significant index to reflect the stability of a UGS salt cavern. The displacement contours for the four caverns are shown in FIGURE 8. By the displacement distribution in the wall rock, the deformation characteristics of each position can be clearly seen. Then a better interpretation for the shape optimization may be concluded.

Based on FIGURE 8, the displacement in the wall rock of the ellipsoid-shape and the irregular-shape caverns is the smallest, while that of cylinder-shape and cuboid-shape caverns is much larger.

1) ANALYSIS OF MAXIMUM DISPLACEMENT

The maximum displacement in the wall rock of the ellipsoid-shape cavern is about 1000 mm and appears in the waist of the cavern, but the area of the large displacement is very small.

The maximum displacement in the wall rock of the irregular-shape cavern is 750 mm and appears in the protuberant part of the waist. The displacement of other protrusion parts is between 600-750 mm. Although the displacement in the wall rock of the irregularly shaped cavern is smaller than that of the ellipsoid-shape cavern, it mainly appears in the protuberant positions of the cavern wall. Therefore, it is

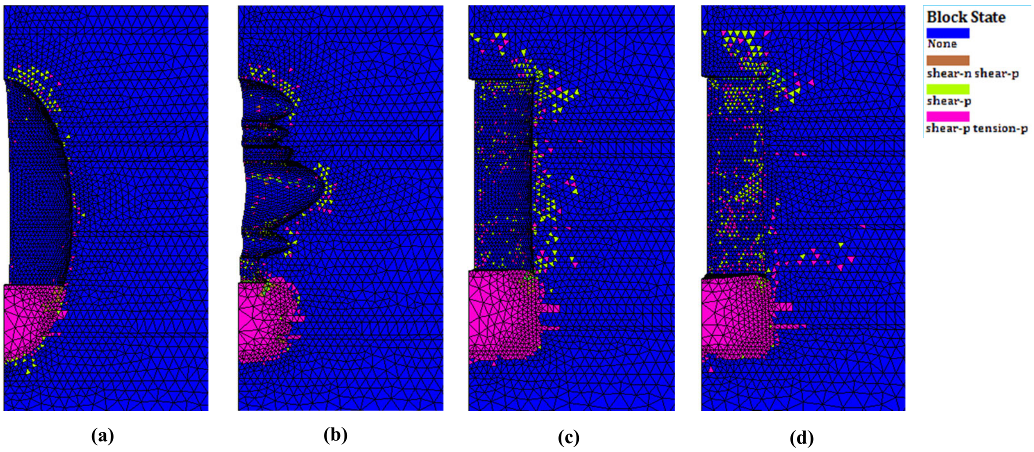

FIGURE 6. Distributions of plastic zones in the wall rock for caverns with different shapes after operating for 30 years: (a) Ellipsoid, (b) Irregular, (c) Cylinder, and (d) Cuboid; Block state stands for the mechanical conditions of the elements in the wall rock.

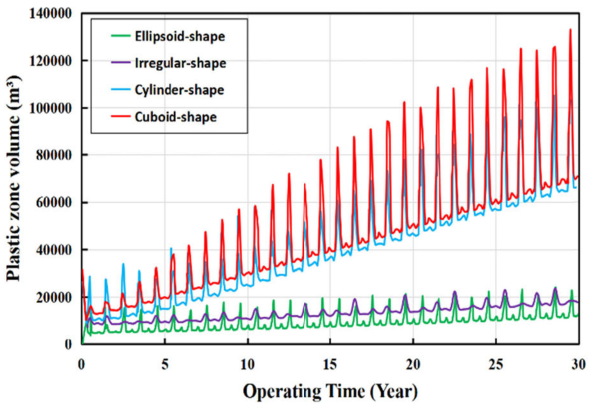

FIGURE 7. Volume of plastic zones for the different-shaped caverns after 30 years of operations.

important to focus on their potential collapse and the adverse effects on the tubings in the cavern.

The maximum displacement in the wall rock of the cylinder-shape cavern is close to 3000 mm and also appears in the waist. Although the area of large displacement is very small, it is 3-4 times larger than that of the first two caverns. This indicates that the stability of this shape cavern is not good, because it leads to huge deformation in the wall.

The maximum displacement in the wall rock of the cuboid-shape cavern is close to 3600 mm, the largest of all different shaped caverns, and it also appears in the waist. Such a large displacement may result in breaking off pieces, collapse, and even cause pillar instability.

By comparison, the wall rock deformation of the first two shape caverns is relatively small. The protuberant positions of the irregular-shape cavern are mainly in the hard interlayer, which has restricted the shrinkage of wall rock in the horizontal direction. The presence of protuberant positions are favorable for cavern stability, but large deformations still appear in these areas. The interlayer is generally the mudstone, which has obvious brittleness and less deformation resistance than salt rock. Therefore, these parts are prone to collapse and pose potential dangers to inner tubings.

2) ANALYSIS OF ROOF DISPLACEMENT

The maximum displacement in the wall rock of all the four differently shaped caverns appear at the waist, but the roof of the caverns is also worthy of close attention. In FIGURE 8, the roof displacement of the four different shape caverns is 580 mm, 550 mm, 1,355 mm and 1,415 mm, respectively. The roof displacement of the ellipsoid-shape and the irregular-shape cavern is about the same, with only about a 5% difference between them. The displacement of the cylinder-shape cavern is close to that of the cuboid-shape cavern, with less than 5% difference. In view of roof safety, cylinder-shape cavern and cuboid-shape cavern are very adverse; their average deformation is 2.5 times larger than that of the irregular-shape cavern and the ellipsoid-shape cavern. This will significantly reduce the safety of these caverns

Comparing the irregular-shape cavern to the ellipsoid-shape cavern, though the wall rock of the former is very irregular with plastic zone and deformation concentrating on the protuberant part, its roof displacement is about the same with that of the ellipsoid-shape cavern. Both of these caverns have an arch roof. Besides, even though the wall rock of the cylinder-shaped cavern is very regular, it does not have a stable roof structure due to its flat roof, so its roof displacement is much larger than that of the first two caverns. The cuboid-shape cavern has the same problem. Although the shape of the wall is square, the edges may lead to stress concentration and intensify local failure; however, the increase in roof deformation is not obvious.

Combining displacement of wall rock and displacement of the roof can fully explain that the design of roof shape is more important than that of wall shape in cavern design. In order to reduce the deformation of the wall rock, the roof of caverns must be designed as an arch. And even if there are some local deformities in the wall, which may affect the deformation, the effects are far inferior to the effect of the

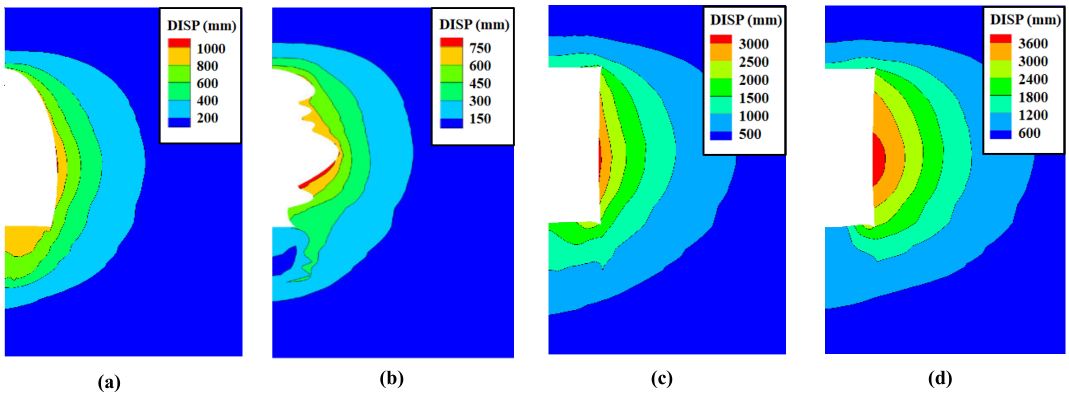

FIGURE 8. Displacement contours around the different-shaped caverns after 30 years: (a) Ellipsoid, (b) Irregular, (c) Cylinder, and (d) Cuboid.

roof shape. Besides, the three indexes show that caverns with a flat roof are not stable. Due to the lack of the roof arch effect, tensile failure and large roof subsidence may occur in the roof. In addition, the overburden pressure is not released and transferred to the pillar, which may result in a huge pillar deformation. Moreover, the stress concentration and damage intensify in the contact corner of the pillar and roof. Therefore, we do not recommend that gas storage caverns have a flat roof or huge plane roofs. For caverns used for brine extraction, or during cavern construction, when being dissolved near the roof, to ensure the cavern stability in later use, we advise controlling the dissolution with an oil or gas blanket to ensure the shape of an arch roof.

IV. CHANGING OPERATING PRESSURE AND UTILIZATION WAYS

A. CHANGING GAS PRESSURE OR SWITCHING TO STORE OIL

If a cavern has an arch-shaped roof and an irregular wall, the potential collapse of the overhanging blocks will have almost no potential risk to the tubings in the cavern. This type of irregularly shaped cavern has no need to be repaired. If we want to use this type of cavern, we only need to change the operating gas pressure or we can also use them for oil storage.

1) INCREASING OPERATION GAS PRESSURE

Three main factors largely determine the stability of UGS salt caverns: geo-conditions, cavern geometries, and operating conditions. After a salt cavern is designed to store natural gas, the sole factor that the human can control is the gas pressure. Once large deformation or volume shrinkage occurs, the operator can increase the gas pressure and decrease the injection-withdrawal frequency to improve the stability of the cavern. From our previous study [33], we identified that the minimum gas pressure (both the value of the minimum gas pressure and its duration) has the most obvious effect on the volume shrinkage rate. So in this study, for the irregular cavern, we suggest increasing the minimum gas pressure to constrain the cavern's deformation rate and thus to improve its stability. To identify this idea, we designed

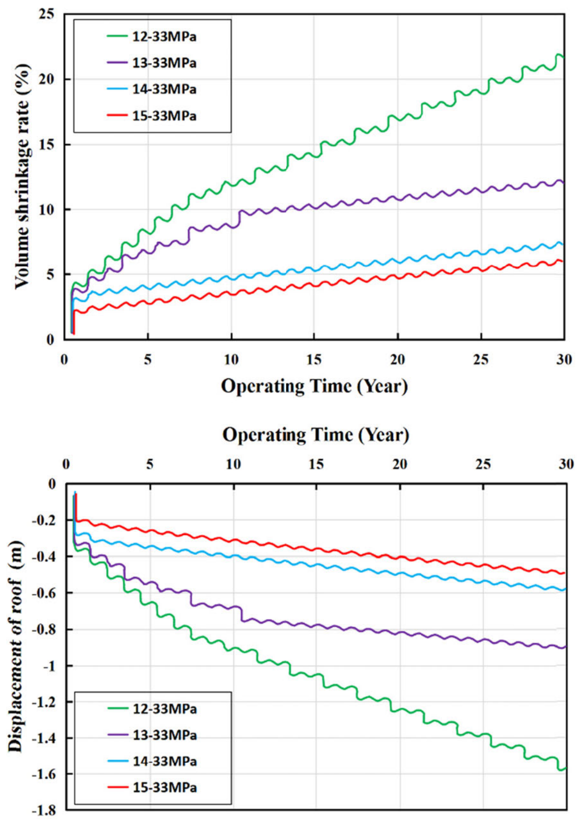

FIGURE 9. Volume shrinkage rate and displacement of the roof under four different operating gas pressure cycles (12-33MPa, 13-33MPa, 14-33MPa, 15-33MPa).

four different operating plans, with minimum and maximum operating pressures of 12-33 MPa, 13-33 MPa, 14-33 MPa, and 15-33 MPa.

FIGURE 9 shows the volume shrinkage rate (VSR) and displacement at the center of the cavern roof for the four operating plans. Increasing the minimum gas pressure P_{min} is really effective to improve the stability of a UGS salt cavern. For instance, when $P_{min} = 12$ MPa, VSR equals 21.5 %, and the roof displacement equals 1.6 m. However, when $P_{min} = 15$ MPa, VSR and roof displacement decrease

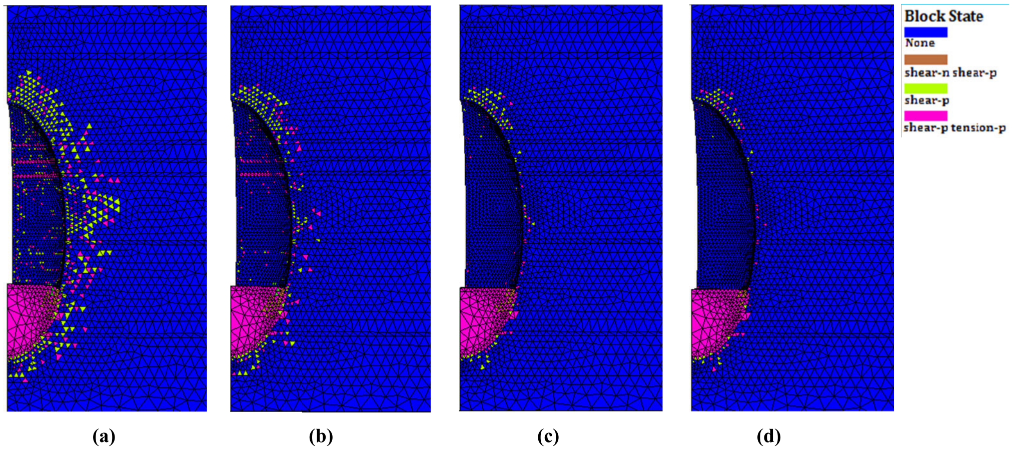

FIGURE 10. Plastic zones in the wall rock under four different operating gas pressure cycles (MPa): (a) 12-33, (b) 13-33, (c) 14-33, and (d) 15-33.

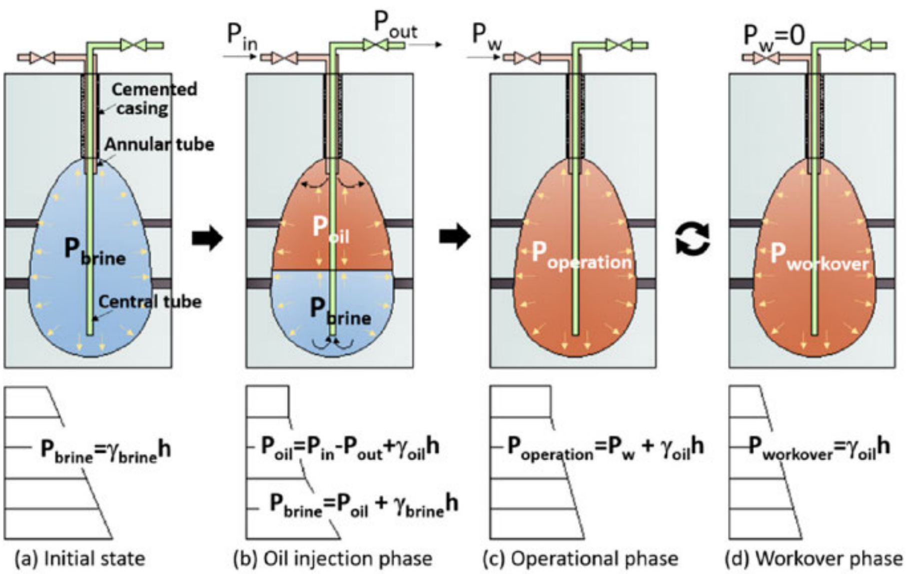

FIGURE 11. Internal oil pressure in the cavern during different stages [40]: (a) Initial state, (b) Oil injection phase, (c) Operational phase, and (d) Workover phase; In this figure, γ_{brine} and γ_{oil} are gravity density of brine and oil, P_{oil} and P_{brine} are the pressure of oil and brine in the cavern, $P_{operation}$ and $P_{workover}$ are the internal pressure in the cavern during operation and workover stages, P_W is pressure applied at the well-head, h is the depth from the ground surface to the cavern roof.

to 6.0% and 0.55 m, respectively, as low as 27.9% and 34.3% of the former values. FIGURE 10 shows the plastic zones of the four cases. When P_{min} = 12 MPa, many plastic zones appear in the roof and waist of the cavern wall. But when P_{min} is increased to 15 MPa, there are no plastic zones in the wall rock and only a few in the roof. These simulation results confirm that the increase in P_{min} is a promising method to improve the stability of a cavern. In this way, the working gas volume will be reduced to a certain extent. When P_{min} is increased from 12 MPa to 15 MPa, the working gas volume is reduced by about 17%. However, even though the construction cost of a salt cavern is rather high, on the whole, the economic benefit of using a salt cavern for gas storage is still much higher than the economic loss caused by the reduction of working gas volume.

2) USING AS AN OIL STORAGE CAVERN

This type of caverns can also be used as a strategic oil storage space. This is because when oil is stored in a salt cavern, the pressure of oil in the cavern remains almost constant because the oil will only be withdrawn during emergencies [40], [51]. There is no cyclic internal pressure variation in the cavern. By the above study in Section 3, it was found that the increase of plastic zones in the wall mainly occurred during the low-pressure period. Therefore, the increase of plastic zones can also be well controlled in an oil storage cavern. Even in the oil-extraction period, the stability of the cavern can be ensured as the oil is displaced by brine injection with a higher pressure. Abroad, there are many cases of using irregular-shaped caverns for oil storage. For instance, the W-6 cavern in West-Hackberry SPR base has a plane roof with a horizontal

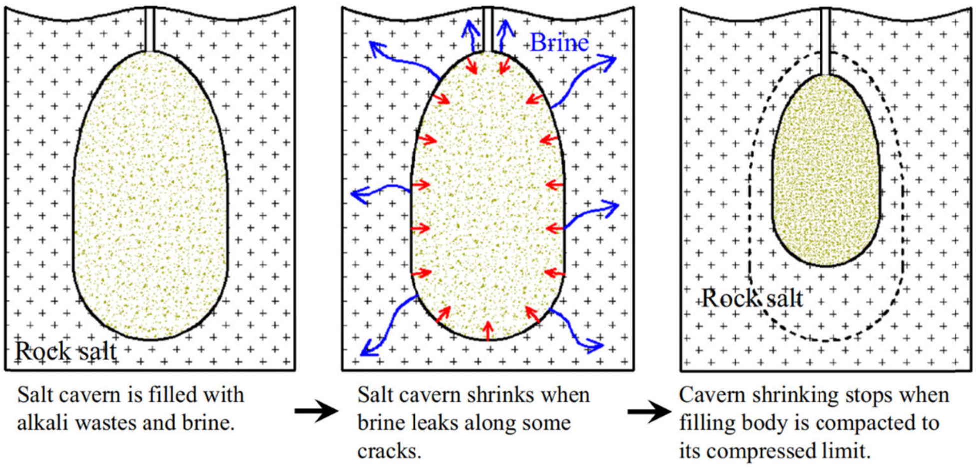

FIGURE 12. Schematic diagram of the process of filling a cavern with waste to control cavern shrinkage (Drawn according to our previous study [55]).

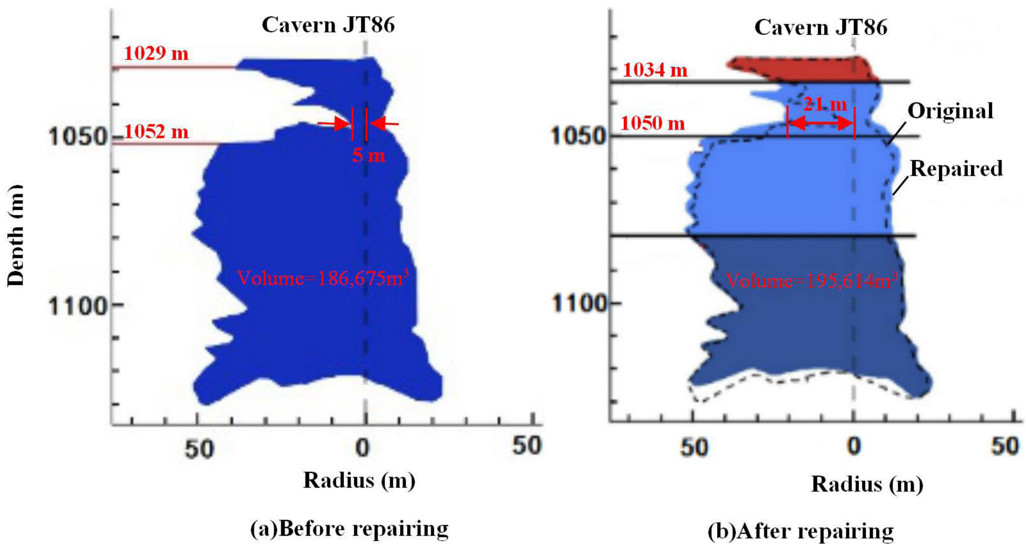

FIGURE 13. The sonar-measured outlines of the JT86 salt cavern before and after modification by a gas-blanket method (Edited based on [56]).

span of 400 m, but it has successfully stored crude oil for over three decades [44]. In addition, oil is much more viscous than natural gas, and it almost cannot leak into the wall rock. As there is no pore-pressure in the wall rock, this is important to ensure the stability of the wall rock. FIGURE 11 shows the internal pressure variation for an oil-storage salt cavern at different stages of the operations.

B. CAVERNS FOR NONHAZARDOUS WASTE DISPOSAL

If the caverns have potential safety hazards, such as small pillar width between adjacent caverns, roof lacking protective salt formation, and the possibility of a large-scale collapse in the wall rock, it would be very unsafe to use them to store oil or gas. For a large cavern with a flat roof, the salt of the roof is prone to collapse, resulting in exposure of mudstone caprock and contact with brine. If erosion and softening of mudstone caprock in brine cause further collapse, it may affect the casing shoe or cement sheath, and then lead to brine leakage. Once a brine leakage occurs, the pressure in the cavern will decrease, and then lead to faster shrinkage. In a serious situation, this may lead to the collapse of the overlying salt formation, excessive surface subsidence, collapse pit and softening of overlying formations by brine [52]. Most of the salt mine collapse accidents in the world have been caused by roof instability and brine leakage [52]–[54]. Large collapse in the wall rock is unacceptable for oil and gas storages, and oil and gas leakage in these caverns will result in catastrophic consequences.

For these caverns, it can be considered to fill them with nonhazardous waste before damage starts or is not serious, and replace brine with wastes. Even if the caverns shrink, the waste fill can control surface subsidence and collapse [55]. FIGURE 12 is a schematic diagram of this application. It can not only prevent the deformation and control subsidence of overlying formations but also allows them to dispose

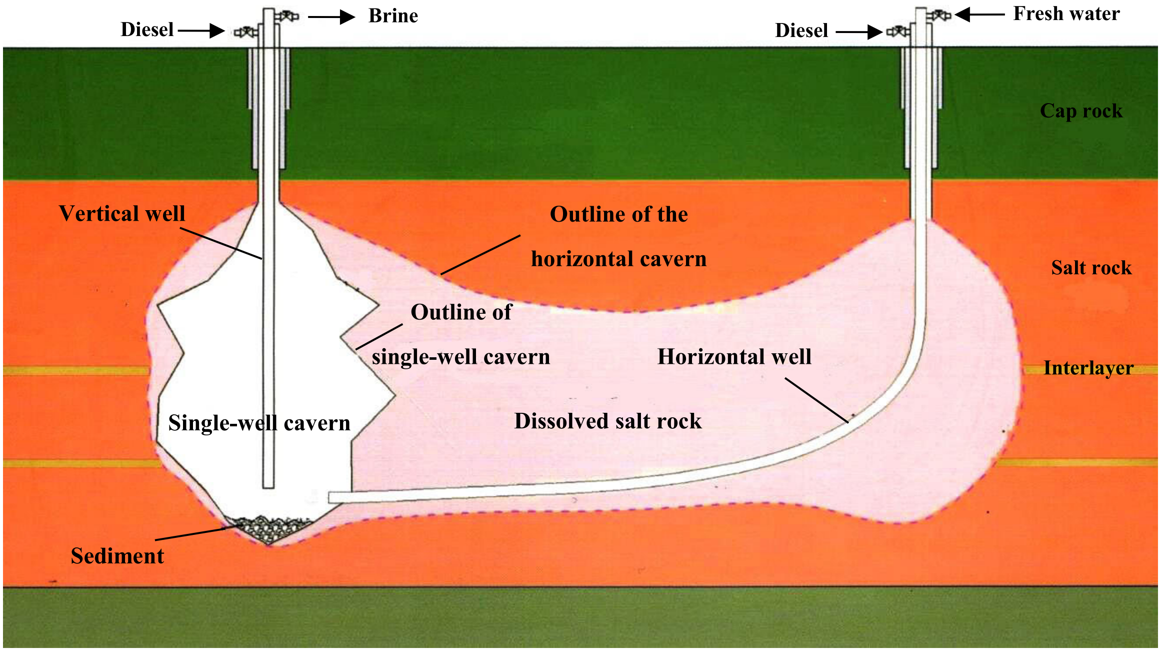

FIGURE 14. Illustration of reconstructing a single-well cavern to a two-butted-well horizontal cavern.

of the waste. Besides, in a mining area with many caverns, it also makes a very good local reinforcement and is beneficial to the stability of regional strata.

V. REPAIRING OR MODIFYING CAVERN SHAPES

The shape of the irregular cavern is not limited to the above, and sometimes the use of a malformed cavern is very difficult. Therefore, it may be necessary to modify the cavern shape. Two typical modifying methods are put forward for practical engineering reference.

A. GAS-BLANKET METHOD

For the cavern with protuberances in the wall, the potential hazard of the protuberant part(s) should be eliminated. When adopting an oil cushion method to repair the wall, the amount of oil cushion is huge, and it is obviously not economical to justify such a repair. High-pressure gas can be used to repair the wall. FIGURE 13 illustrates an example of using the gas-blanket method to modify the cavern shape [56]: the repair was completed in May 2016. According to the sonar imaging data on June 8, 2016, the volume of the cavern is about 195,614 m^3. Compared with the original cavern, the volume of Cavern JT86 has increased by about 8,939 m^3, and the minimum radius of the south part has increased to about 21 m.

B. MODIFYING A SINGLE-WELL CAVERN TO A TWO-BUTTED-WELL HORIZONTAL CAVERN

If a single-well cavern's shape is too irregular and it is difficult to implement a cavern repair, we can consider the modifying of a single-well cavern into a two-butted-well horizontal cavern, as shown in FIGURE 14. Regarding the existing single-well cavern as the target well, we can drill a horizontal well from a certain distance (100-300 m is recommended) away from it to connect with the single-well cavern. Freshwater is injected into the horizontal well for mining, and the original single-well can be used as a brine extraction channel. The caverns can be constructed as a horizontal segment by cutting away the pipe orifice (keeping the location of the pipe orifice back) in a horizontal well. In this way, a regular large volume horizontal cavern can be built in the formation to make use of single wells and caverns that otherwise may need to be abandoned. Due to the large volume and regular shape, then we can store more gas in the cavern and the cavern stability will improve.

VI. CONCLUSION AND SUGGESTIONS

(1) According to the characteristics of bedded salt rocks and the characteristics of cavern construction techniques, four typical caverns with different shapes were designed, ellipsoid-shape, irregular-shape, cylinder-shape, and cuboid-shape caverns. A numerical calculation model of the caverns is established and gas storage simulations are carried out.

(2) Three indexes that describe cavern stability are selected as the criteria for determining the stability of UGS caverns, namely volume shrinkage, plastic zone, and surrounding rock displacement. The results show that the indexes of the cylinder-shape cavern and the cuboid-shape cavern are relatively large, indicating that these cavern shapes are less desirable. The irregular-shape cavern has the minimum stability concerns due to the deformation restriction by interlayer, but the influence of local damage should be paid close attention to. The indexes of the ellipsoid-shape cavern are much smaller those that of cylinder-shape and cuboid-shape caverns, and slightly higher than that of the irregular-shape cavern.

(3) The effect of roof shape on stability is more significant than that of wall shape. The cavern with a flat roof will lead to large deformation of the cavern and failure of the large plastic area, while an arched roof can greatly reduce the deformation and improve the stability. Local malformed sidewalls have a significant influence on local stability but little influence on overall stability. Therefore, we strongly suggest to design and construct the cavern roof as an arch shape.

(4) For the cavern with small protuberances in the wall, we suggest to increase the minimum internal operating gas pressure and reduce the injection-production frequency to improve the stability, or use the cavern to store oil to improve the cavern safety. For the cavern with a flat roof, it is suggested to fill it with alkali waste to eliminate any potential geological risks. For a cavern with large over-hanging blocks in the wall, we can consider the gas-blanket method to repair the cavern shape, or we can reconfigure the single-well cavern to be a two-butted-well horizontal cavern by drilling and operating a horizontal well, too.

In this study, the long-term stability of natural gas storage in typically irregular shaped caverns was compared and the key factors that affect the stability of various cavern geometries were identified. However, there are still some deficiencies in this study, such as the lack of simulations based on the more actual internal gas pressure variation in a cavern, and shape optimization using some optimization algorithms [57]–[60]. These problems will be addressed in future research.

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