Instability risk analysis and risk assessment system establishment of underground storage caverns in bedded salt rock

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Abstract. Stability is an important part of geotechnical engineering research. The operating experiences of underground storage caverns in salt rock all around the world show that the stability of the caverns is the key problem of safe operation. Currently, the combination of theoretical analysis and numerical simulation are the mainly adopts method of reserve stability analysis. This paper introduces the concept of risk into the stability analysis of underground geotechnical structure, and studies the instability of underground storage cavern in salt rock from the perspective of risk analysis. Firstly, the definition and classification of cavern instability risk is proposed, and the damage mechanism is analyzed from the mechanical angle. Then the main stability evaluating indicators of cavern instability risk are proposed, and an evaluation method of cavern instability risk is put forward. Finally, the established cavern instability risk assessment system is applied to the analysis and prediction of cavern instability risk after 30 years of operation in a proposed storage cavern group in the Huai’an salt mine. This research can provide a useful theoretical base for the safe operation and management of underground storage caverns in salt rock.

1. Introduction
Stability is an important part of geotechnical engineering research, and it is closely related to the safety in the construction and operation of underground projects. Many achievements in the stability research of geotechnical engineering have been made since 1950s, such as elastic analysis and elastic-plastic analysis (limit equilibrium) of tunnels, complex function analysis of elastic plane problems of surrounding rock, block mechanics analysis of the stability of surrounding rock, methods and techniques of supporting soft rock, as well as the numerical analysis methods of stability.

Salt rock is a special type of soft rock. The operating experiences of underground storage caverns in salt rock all around the world show that the stability of the caverns is the key problem of safe operation [1]. Many accidents, such as oil or gas leakage, ground subsidence and cavern failure, are caused by cavern instability essentially. Scholars in China and abroad have intensively researched the stability of underground storage caverns in salt rock. Staudtmeister et al. [2] analyzed the safety of underground storage caverns using a numerical analysis method. Dusseauit et al. [3,4,5] researched the safety and reliability of the salt caverns storing poisonous and radioactive solids. Yu Hailong et al. [6] studied the stability of underground caverns in salt rock by similar material experiment. Wu Wen et al. [7] proposed evaluation criteria of the stability of storage caverns in salt rock based on theoretical...
analysis and numerical simulation. Yang Chunhe et al. [8] researched the feasibility of energy storage in bedded salt rock. Jiang Deyi et al. [9] studied the stability of underground caverns using catastrophe theory. Xu Suguo [10] researched on the cavern stability in the process of cavern deformation. Ren Song [11] built up a comprehensive evaluation system of the stability during operation of gas storage caverns in bedded salt rock based on an Analytic Hierarchy Process. Jiang Deyi [12], Yin Xueying et al. [13], Zhao Kelie [14] researched the influence law of some factors on the stability of storage caverns in salt rock. As there are few projects of underground storage cavern in bedded salt rock in China, and as their operating life until now is very short, the main research method of stability is theoretical analysis combined with numerical simulation.

This paper introduces the concept of risk into the stability analysis of underground geotechnical structure, and studies the instability of underground storage cavern in salt rock from the perspective of risk analysis. Firstly, the definition and classification of cavern instability risk is proposed, and the damage mechanism is analyzed from the mechanical angle. Then the main stability evaluating indicators of cavern instability risk are proposed, and an evaluation method of cavern instability risk is put forward. Finally, the established cavern instability risk assessment system is applied to the analysis and prediction of cavern instability risk after 30 years of operation in a proposed storage cavern group in the Huai’an salt mine. This research can provide a useful theoretical base for the safe operation and management of underground storage caverns in salt rock.

2. Definition and classification of cavern instability risk

2.1. Definition of cavern instability risk

The stability of geotechnical engineering structures means that during construction and service the underground cavity should keep the predetermined size and shape, and meet other availability requirements. According to this, the instability risk of storage caverns in bedded salt rock is defined as follows:

During construction and operation, the surrounding rock of the storage caverns may break unexpectedly, or the rock deformation may exceed the safe convergence value, and finally cause the caverns not to be constructed or operated normally.

Cavern instability risk is one of the common risks of underground storage caverns in salt rock, both during construction and during operation. It will break the internal facilities, and even cause secondary disasters, such as oil or gas leakage, ground subsidence and cavern failure. This kind of accident may result in economic losses, construction delays, and even in the cavern being discarded, potentially at a great loss. Therefore, it is very necessary to carry out research on cavern instability risk analysis and prediction of storage caverns.

2.2. Classification of cavern instability risk

2.2.1. Classification according to the influence extent  According to the influence extent, the cavern instability risk can be classified into the risk of local instability or the risk of global instability.

Local instability means that failure or collapse occurs in a local section of the surrounding rock. This type of accident will generally break the pipe string in the cavern, or delay the construction, but may not immediately result in global collapse. In this case, the cavern will continue to be used for a sufficient period.

Global instability means the global equilibrium of a cavern is broken caused by the collapse of the cavern roof or pillar. This kind of accident will immediately result in the cavern being abandoned.

2.2.2. Classification according to the location of instability  Depending on where an instability develops, the cavern instability risk can be classified as a roof instability risk, a bottom instability risk, a sidewall instability risk or a pillar instability risk.
Because of the presence of structural planes between the rock strata, and the free faces and cracks induced by the local stress concentration at the top of the cavern, part of the surrounding rock may fall down under gravity. The possibility of this kind of accident is called roof instability risk.

Under the high local stress, the rock at the bottom or sidewall may crack, bulge or peel off. The possibilities of these two kinds of accidents are respectively called bottom instability risk and sidewall instability risk.

The plastic zones of a pillar may connect when the difference in pressures between neighboring caverns is large. This may lead to pillar failure, as the pillar no longer can bear the loads imposed on it. The possibility of this kind of accident is called pillar instability risk.

3. Mechanisms of cavern instability

Generally speaking, the instability of underground cavities is caused mainly by the failure or excessive deformation of the surrounding rock under the secondary stress during or after excavation. From the mechanical point of view, the reason for instability is that stress in the surrounding rock exceeds the rock mass strength. Then extensive continuous plastic zones and numerous fracture planes appear. Finally large deformation of the surrounding rock or rock failure occurs. According to engineering geology theory and rock mechanics, the mechanism of surrounding rock failure can be considered to be of three types: tension failure, shear failure, or fatigue failure.

3.1. Tension failure

As the internal pressure of a storage cavern is always lower than the in-situ stress during construction and operation and the salt rock has obvious creep properties, the surrounding rock will continuously move toward the center of the cavern. If the deformation of the cavern wall is not uniform, local bulging and squeeze-out will appear. This type of failure depends on the tensile strength and shear strength of the surrounding rock.

When the stress concentration around the cavern exceeds the tensile strength of the surrounding rock, cracks and fractures will develop in the rock mass near the cavern. The surrounding rock with many cracks and fractures is unstable and might easily collapse under the secondary stress.

3.2. Shear failure

After the cavern is formed, the stress nearby will redistribute and stress concentration zones will appear near the cavern. In the stress concentration zones, the shear stress is several times larger than the original stress. When the shear stress exceeds the shear strength of the surrounding rock, the rock may fail in shear at some location. Shear fissures may appear and the integrity of the surrounding rock may be damaged. Similarly as for tension failure, the surrounding rock with cracks and fractures may easily collapse under the secondary stress.

3.3. Fatigue failure

Fatigue failure means that the material fails under a repeated or cycling stress which is far lower than its instantaneous strength when bearing alternating load.

When the salt caverns are used for short-term energy storage or peak regulation of energy supply, the surrounding rock of the caverns will bear alternating load during the cycles of gas or oil injection and withdrawal. As the long-term strength of rock (about 30% of the instantaneous strength) [15] is far lower than its instantaneous strength, the surrounding rock will fail much more easily when subjected to alternating load, especially the pillars between the caverns.

4. Evaluating indicators of cavern instability risk

The phenomenon of local instability and global instability is hard to be observed. Therefore, most of the stability researches of the storage cavern in salt rock are carried out using numerical simulation. Based on the research achievements and numerical simulation method, it is proposed to use the extent
of plastic zones, the displacement of the cavern wall, and the deformation rate of the surrounding rock as the evaluating indicators in order to evaluate and predict the instability risk at some stage.

4.1. Extent of the plastic zones
The extent of the plastic zones around the cavern is an important evaluating indicator of cavern instability risk. The in-situ stress near the cavern will redistribute after the cavern is formed and the stress concentration zones will appear in the surrounding rock near the cavern. Therefore, the rock near the cavern wall may reach its ultimate strength, enter the plastic state, and then fail. After that, the low stress zones will appear near the cavern wall because of the stress release following along with the cavern wall failure. Then the stress concentration zones transfer inward into the surrounding rock, so the plastic zones and failure zones expand inward too.

Although the plastic zones do not equal the failure zones, the failure zones are included in the plastic zones. The further the boundary of the plastic zones from the cavern wall, the higher the local stresses near the stress concentration zones. In this case, there is a high probability of the rock near the cavern wall to fail. Assuming that the distance between the boundary of the plastic zones and the cavern wall is \( S \), and the diameter of the cavern is \( D \). The ratio \( S/D \), which is expressed by \( P_1 \), can be seen as an evaluating indicator of the cavern instability risk.

As the pillars between neighboring caverns is the weak link and easy to be damaged, the upper limit value of the plastic zone scope is reached when the plastic zones of the two sides of a pillar connect with each other.

In general, the width of the safety pillar is decided by the following formula:

\[
B = KD
\]

Where \( D \) means the diameter of the cavern, \( K \) means the safety coefficient, the range of \( K \) in Germany is 1.5~6.0 [16], in the USA it is 1.75~2.5 [17].

In order to guarantee the safety of the storage cavern during construction and operation, and improve the utilization of salt rock at the same time, the general range of \( K \) is 1.5~2.5 in China. From a safety point of view, here \( K=1.5 \). The evaluation criteria of \( P_1 \), which means the ratio of the distance between the boundary of the plastic zones and the cavern wall to the diameter of the cavern, are listed in Table 1.

| Degree of risk | Degree 1 | Degree 2 | Degree 3 | Degree 4 |
|----------------|---------|---------|---------|---------|
| Description of risk | Instability nearly impossible to happen | Instability less likely to happen | Instability possible to happen | Instability probable to happen |
| Extent of indicator | \( P_1 \leq 0.25 \) | \( 0.25 < P_1 \leq 0.5 \) | \( 0.5 < P_1 \leq 0.75 \) | \( P_1 > 0.75 \) |
| Acceptance criteria | Negligible | Acceptable without taking precautions | Acceptable with taking precautions | Unacceptable |

4.2. Displacement of the cavern wall
As salt rock has obvious creep properties, the caverns in salt rock will be able to remain stable even when the surrounding rock undergoes large deformation. Considering the requirements of stability and usability, there should be an upper limit of the surrounding rock deformation. According to the criteria which are accepted internationally, when the volume shrinkage rate of a storage cavern in salt rock reaches up to 30%, the cavern is thought to lose most of its functionality, and can no longer meet the demands of cavern stability [18].

Therefore, \( P_2 \), which means the ratio of the displacement of the cavern wall to the cavern diameter, is seen as an evaluating indicator of the cavern instability risk. In order to simplify the calculation, the shape of the cavern is assumed to be spherical. The upper limit value of \( P_2 \) is calculated in the case that the volume shrinkage rate of the cavern reaches 30%. From a safety point of view, 0.06 is taken as the upper limit value of \( P_2 \). The evaluation criteria of \( P_2 \) are listed in Table 2.
**Table 2.** Criteria of the cavern wall displacement for evaluating cavern instability risk.

| Degree of risk | Degree 1                  | Degree 2                  | Degree 3                  | Degree 4                  |
|----------------|---------------------------|---------------------------|---------------------------|---------------------------|
| Description of risk | Instability nearly impossible to happen | Instability less likely to happen | Instability possible to happen | Instability probable to happen |
| Extent of indicator | $P \leq 0.02$ | $0.02 < P \leq 0.04$ | $0.04 < P \leq 0.06$ | $P > 0.06$ |
| Acceptance criteria | Negligible | Acceptable without taking precautions | Acceptable with taking precautions | Unacceptable |

4.3. **Deformation rate of the cavern**

The deformation rate is also an important evaluation indicator of cavern stability. The creep of rock salt can be separated into three phases: initial creep, steady state creep, and accelerated creep. If the operating time is very long or the control of operating parameters is improper (such as the operating time under low pressure is very long, gas or oil injection and withdraw is very frequent, and so on), the rock surrounding the cavern may enter into the accelerated creep phase. In this phase, the creep rate of the salt rock increases markedly and the mechanical properties deteriorate rapidly. When the surrounding rock bears continuous pressure, the cracks in the rock will extend and the stability of the cavern will decrease. Therefore, the high deformation rate of the surrounding rock may be accompanied by the deterioration of mechanical properties and crack extension. The cavern instability risk increases quickly at this time.

The annual cavern shrinkage rate is an indicator of the cavern deformation rate. At the initial operating stage of the storage cavern, the creep rate of the surrounding rock is quite high. It is generally accepted that the cavern shrinkage rate after 5 years running should be controlled to within 5%. So the annual shrinkage rate should be lower than 1%. This is taken as the upper limit value of $P_3$, which means the annual cavern shrinkage ratio during a certain period. The evaluation criteria of $P_3$ are listed in Table 3.

**Table 3.** Criteria of the annual cavern shrinkage rate for evaluating cavern instability risk.

| Degree of risk | Degree 1                  | Degree 2                  | Degree 3                  | Degree 4                  |
|----------------|---------------------------|---------------------------|---------------------------|---------------------------|
| Description of risk | Instability nearly impossible to happen | Instability less likely to happen | Instability possible to happen | Instability probable to happen |
| Extent of indicator | $P \leq 0.33\%$ | $0.33\% < P \leq 0.67\%$ | $0.67\% < P \leq 1\%$ | $P > 1\%$ |
| Acceptance criteria | Negligible | Acceptable without taking precautions | Acceptable with taking precautions | Unacceptable |

5. **Risk assessment system of cavern instability**

5.1. **Establishment of the assessment system**

Based on the analysis of the definition, the failure mechanisms, and evaluating indicators of cavern instability risk, the assessment system is built as Figure 1.
5.2. Description of the risk assessment system

According to Figure 1, the cavern instability risk of the storage caverns in bedded salt rock includes four evaluation criteria: roof instability risk, bottom instability risk, sidewall instability risk, and pillar instability risk. Each evaluation criterion should be evaluated by three indicators: extent of the plastic zones, displacement of the cavern wall, and cavern deformation rate during a certain period. If one of the four types of risk happens, it means that the cavern instability risk takes place. Only if all the four types of risk have very low risk grade will the cavern instability risk be very low. Therefore the risk level of the cavern instability risk should be decided by the type of instability risk with the highest risk level.

6. Case analysis of risk prediction of cavern instability

By means of numerical simulation, the instability risk of a gas cavern group which is proposed to be developed in Huai’an salt mine in China is analyzed after running for 30 years.

6.1. Modeling

6.1.1. Strata and cavern model According to the geological investigation report of the Huai’an salt mine, the strata here are a thin layered structure with salt rock and mudstone. The number of layers is large. Many mudstone interlayers are very thin (less than 1.5m). The roof depth of the cavern has been decided to be -1336m, the bottom depth is -1478m, hence the height of the cavern is 142m. The shape of the cavern is ideally designed to be semielippsoidal in the upper part and semispherical in the lower part. The origin of the coordinate system is located at the point on the ground surface directly above the center of the cavern. The horizontal plane is the XY plane of the coordinate system, and the vertical direction is the Z axis. The strata model is built from -838 m to -1738 m. The weight of the strata above -838 m is simplified to be the vertical load applied on the upper surface of the model. The average density of the strata is 2.3 g/cm³. The in-situ stress field is considered to be a triaxial equi-compressional gravity field. The lower surface of the model is fixed by simply supported constraints in the Z direction. The four vertical surfaces are fixed by simply supported constraints in X or Y direction correspondingly. Figure 2 is the strata and cavern model of one cavern.
Figure 2. Strata and cavern model of one cavern.

The software ANSYS and FLAC3D are used to establish the calculation model. The shape of the cavern and the mesh generation near the cavern are shown as Figures 3 and 4.

Figure 3. Shape of the cavern.  Figure 4. Mesh generation near the cavern.

6.1.2. Mechanical parameters  Based on the results of experiments on rock samples from this area, the basic mechanical parameters of salt rock and mudstone are listed in Table 4.

| Rock type  | Elastic modulus /GPa | Poisson ratio | Cohesive strength /MPa | Angle of internal friction /° | Tensile strength /MPa | A/(MPa^{-3.5}·a^{-1}) | n  |
|------------|----------------------|---------------|------------------------|------------------------------|-----------------------|------------------------|----|
| Salt rock  | 5.05                 | 0.29          | 4.21                   | 37.6                         | 0.63                  | 1.5×10^6               | 3.5|
| Mudstone   | 6.22                 | 0.30          | 3.22                   | 36.4                         | 0.62                  | 5×10^8                 | 3.5|

Where A and n are the creep test constants of salt rock.
6.1.3. Distribution of cavern group  The caverns in a cavern group have been planned to be distributed as shown in Figure 5. In this case, the distribution of the stress field of a cavern will be affected by the four neighbouring caverns. As the distribution of the caverns is symmetrical, the modeling range is selected as the part with shadow in Figure 5. According to the feasibility study report of gas storage caverns in Huai’an salt mine, the width of the pillar is 1.5 times the cavern diameter (120 m), and the average operating pressure is 15.5 MPa (the suggested pressure range is 9–22 MPa). The calculation model near the cavern is shown in Figure 6.

![Figure 5. Cavern distribution and area selected (shaded)](image5)

![Figure 6. Calculation model near the cavern](image6)

6.1.4. Constitutive model  The classical Mohr-Coulomb strength criterion is used during the elastoplastic calculation. It is suitable to describe the shear failure of both plastic rock and brittle rock.

In the creep calculation, the constitutive equations of the creep strain rate of salt rock during the steady creep phase are as follows:

\[
\dot{\varepsilon}(t) = A q^n
\]  

(2)

Where \( q = \sqrt{3J_2} \) \( (J_2 = 1/2S_{ij}S_{ij}) \) is the Second Invariant of the stress deviator; \( A, n \) are the main creep parameters of salt rock.

The plastic strain and plastic failure follow the Mohr-Coulomb flow rule and Mohr-Coulomb yield criterion.

6.2. Analysis of the computing results  The distribution of the plastic zones and the displacement near the cavern after 30 years of operations are shown in Figures.7 and 8.

![Figure 7. Plastic zones distribution near the cavern after 30 years of operations.](image7)

![Figure 8. Displacement field distribution near the cavern after 30 years of operations.](image8)
6.2.1. Analysis of the plastic zones  

Seen from Figure 8, the analysis of cavern instability risk is as follows:

1) At the top of the cavern, the extent of the plastic zones is small, and the maximum distance between the boundary of the plastic zones and the cavern roof is about 10m. According to the description of the evaluating indicators $P_1$ in Section 3.1,

$$ P_1 = \frac{10}{80} = 0.125 $$

According to Table 1, after 30 years of operations, the risk degree of roof instability is Degree 1, which means the occurrence probability of the roof instability is very low, and the risk is negligible.

2) At the shoulder of the cavern, the maximum distance between the boundary of the plastic zones and the cavern sidewall is about 25m. So,

$$ P_1 = \frac{25}{80} = 0.3125 $$

According to Table 1, the risk degree of sidewall instability is Degree 2, the occurrence probability of the sidewall instability is quite low, and the risk is acceptable without taking precautions.

3) At the narrowest region of the pillar between two caverns, the maximum distance between the boundary of the plastic zones and the cavern sidewall is about 12m. So,

$$ P_1 = \frac{12}{80} = 0.15 $$

According to Table 1, the risk degree of pillar instability is Degree 1, the occurrence probability of the pillar instability is very low, and the risk is negligible.

4) The plastic zone at the bottom of the cavern is too small to be observed. Therefore, the risk degree of bottom instability is Degree 1, which means the occurrence probability of the bottom instability is very low, and the risk is negligible.

6.2.2. Analysis of the cavern wall displacement  

Seen from Figure 8, the analysis of cavern instability risk is as follows:

1) The maximum displacement of the cavern wall at the cavern roof is about 3 m. According to the description of the evaluating indicators $P_2$ in Section 3.2,

$$ P_2 = \frac{10}{80} = 0.0375 $$

According to Table 2, the risk degree of roof instability is Degree 2 after 30 years of operations, which means the occurrence probability of the roof instability is quite low, and the risk is acceptable without taking precautions.

2) The maximum displacement of the cavern wall at the cavern shoulder is about 4.01 m. So,

$$ P_2 = \frac{4.01}{80} = 0.0501 $$

According to Table 2, the risk degree of sidewall instability is Degree 3, the occurrence probability of the sidewall instability is quite high, and the risk is acceptable with taking precautions.

3) The maximum displacement of the narrowest region of the pillar is about 3 m. So,

$$ P_2 = \frac{3}{80} = 0.0375 $$

According to Table 2, the risk degree of pillar instability is Degree 2, the occurrence probability of pillar instability is quite low, and the risk is acceptable without taking precautions.

4) As the maximum displacement of the cavern wall at the bottom is too small to be estimated, the risk degree of bottom instability is Degree 1, the occurrence probability of bottom instability is very low, and the risk is negligible.

**Table 5. Cavern shrinkage rates of the cavern during operation.**

| Creep time /year | 0  | 1  | 3  | 5  | 7  | 10 | 12 |
|------------------|----|----|----|----|----|----|----|
| Cavern shrinkage rate /% | 0 | 1.584 | 3.406 | 5.001 | 6.483 | 8.553 | 9.849 |

6.2.3. Analysis of the cavern deformation rate  

As it is very hard to monitor the displacement of every point on the cavern wall, the annual cavern shrinkage rate is taken as the average value of the
deformation rate of the cavern wall. The cavern shrinkage rates of the cavern during operation are listed in Table 5.

Obviously, the cavern shrinkage rate increases as the operating time increases, but the rate of increase increment slows down progressively. According to the cavern shrinkage rate values corresponding to 28 years and 30 years, the average annual cavern shrinkage rate after 30 years of operations can be calculated as follows:

\[ P = \frac{(19.55\% - 18.62\%)}{2} = 0.465\% \]

According to Table 3, considering the deformation rate of the surrounding rock, the risk degrees of roof instability, sidewall instability, pillar instability and bottom instability are all Degree 2 after 30 years of operations, which means the occurrence probabilities are all quite low, and the risks are acceptable without taking precautions.

6.2.4. Comprehensive evaluation of the cavern instability risk

The analytical results according to the extent of the plastic zones, displacement of the cavern wall and the cavern deformation rate are all listed in Table 6.

| Risk degree | Roof instability risk | Bottom instability risk | Sidewall instability risk | Pillar instability risk |
|-------------|-----------------------|-------------------------|--------------------------|------------------------|
| Extent of the plastic zones | Degree 1 | Degree 1 | Degree 2 | Degree 1 |
| Displacement of the cavern wall | Degree 2 | Degree 1 | Degree 3 | Degree 2 |
| Cavern deformation rate | Degree 2 | Degree 2 | Degree 2 | Degree 2 |
| Comprehensive risk degree | Degree 2 | Degree 2 | Degree 3 | Degree 2 |
| Risk evaluation | Instability is less likely to happen, the risk is acceptable without taking precautions | Instability is less likely to happen, the risk is acceptable without taking precautions | Instability is possible to happen, the risk is acceptable with taking precautions | Instability is less likely to happen, the risk is acceptable without taking precautions |

From Table 6, in this engineering case, after 30 years of operations, the risk degree of sidewall instability is much higher than that of roof instability, pillar instability and bottom instability. That is to say, the cavern instability risk is probable to happen in the cavern group after 30 years of operations. More attention should be paid to the sidewall instability risk and some measures should be taken to prevent the occurrence of this kind of accident during operation.

7. Main conclusions

1. The definition of cavern instability risk of storage caverns in salt rock is put forward as follows: during construction and operation, the rock surrounding the storage caverns may break unexpectedly, or the rock deformation may exceed the safe convergence value, and ultimately cause the caverns not to be constructed or operated normally. This type of risk is called cavern instability risk.

2. From a mechanical point of view, the reason for instability is that the stress exceeds the rock mass strength. Then extensive continuous plastic zones and numerous fracture planes appear. Finally large deformation of the surrounding rock or rock breaking occurs. The mechanisms of surrounding rock failure can be considered to consist of three types: tension failure, shear failure and fatigue failure.

3. The extent of the plastic zones near the cavern, the displacement of the cavern wall, and the deformation rate of the cavern are proposed to be the main evaluating indicators to predict and assess
the degree of the cavern stability at some stage. Then the risk assessment system of the cavern instability is established.

4. Taking a salt cavern group at a salt mine in Huai’an as an engineering case, the established risk assessment system is used to analyze the cavern instability risk after 30 years of operations. The result shows that the risk degree of sidewall instability is much higher and some measures should be taken to prevent the occurrence of this kind of accident during operation.

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