Three-Dimensional Mechanical Information Model and Its Application to Large Underground Water-Sealed Storage Caverns for Oil or Gas

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Abstract. This work explores a three-dimensional (3D) mechanical information model for use in the design optimization of large underground water-sealed storage caverns. First, a 3D geological model is built on the basis of the exploration results obtained at the beginning of the exploration stage. Second, a 3D numerical calculation model is established with parameters integrated from various engineering data sources, especially from geophysical explorations and field tests. Finally, the results of the numerical calculation model are used to evaluate the stability and water seal effectiveness of the surrounding rocks. The subsequent analysis of two engineering cases shows the feasibility of the technical method for the design optimization of storage caverns. The method is expected to be improved in the practical construction process in the future.

Key words: Underground water-sealed storage caverns; geological analysis; 3D geological model; mechanical information model; geophysical exploration method;

1. Introduction

Underground water-sealed storage caverns are a type of oil or gas storage facility with hydraulic sealing in low permeability rock mass. The principles of oil and gas storage are the same, but the values of the design parameters of the water sealing systems are different. Given the inherent concealment and uncertainty characteristics of rock mass, the design of underground caverns is mainly based on geological information. The layout plan usually depends on engineering experience in geological analysis, and the support scheme is confirmed though mechanical analysis on several key sections. Furthermore, the design model is based on qualitative analysis and engineering experience and is thus suitable for small- and medium-sized cavern engineering under relatively simple geological conditions. In recent years, the capacity of large underground water-sealed storage caverns has increased from about 2 million to more than 5 million m³, and the scale of excavation practice has expanded accordingly. As an increasing number of geological units should be included in the scope of storage caverns, the geological conditions inevitably become complicated. Given the heavy investments in storage cavern projects, the design scheme should be quantitatively optimized, and geological risks should be avoided. These requirements call for large amounts of detailed geological and mechanical data.

In the field of exploration, drilling is the main data acquisition method by which information about underground rock formations can be directly obtained. However, its actual scope for exposure is limited to drilling regions. The surrounding rock mass around a cavern can be uncovered at the
construction stage, and the involved scope of the rock mass is limited even with a geological sketch and inversion from monitoring data. Meanwhile, the properties of a large scope of rock and soil can be detected through geophysical prospecting, but this method is usually used for qualitative analysis in conjunction with drilling; hence, the valuable engineering data used in the application are not refined. For a site that measures several square kilometers wide, only dozens of boreholes can be relied on, and the basic data available for actual simulation are limited; these limitations obviously affect the precision of the numerical calculation model and its resolution. They also influence the effectiveness of safety evaluation for the surrounding rocks in cavern group engineering.

At present, the international oil price is at a low level and may remain the same for some time. This condition presents a good opportunity to promote the construction of large storage caverns for oil. Carrying out the quantitative evaluation of the mechanical state of surrounding rocks at the cavern group level offers commercial and social significance as it actively ensures construction safety and helps control the construction period.

2. Basic technical framework

Effectively optimizing the design scheme of large underground water-sealed storage caverns requires the refinement of geological and mechanical analyses in terms of storage space. Numerical analysis is a typical design analysis method for rock mechanics and engineering; it can quantitatively calculate the mechanical state of surrounding rocks and has thus been applied to actual engineering design. For high content of modeling technology and the representativeness problems of mechanical parameters, three-dimensional (3D) numerical analysis is generally an auxiliary analysis method. With the continuous improvement of computer software and hardware processing performance, as well as the representativeness problem of mechanical parameters, the 3D numerical method analysis can be used as a powerful means to optimize the design of large cavern groups.

For the design optimization of large underground water-sealed storage caverns, a 3D geological model should be established to check the layout plan. Then, a 3D numerical model for the stability and seepage field of surrounding rocks can be constructed. The mechanical state of surrounding rocks is quantitatively evaluated on the basis of numerical results and other engineering data. A 3D information model can then be formed from the 3D numerical model on the basis of its results, the 3D geological model, and other engineering data. The basic technical framework is shown in Figure 1, and the main components are described as follows.

![Diagram](image)

**Figure 1.** Basic technical framework of quantitative analysis of rock mechanics

2.1 3D geological model

The 3D geological model is used to visually display the 3D morphology (for visualization), calculate the size and orientation of the geological body (for geological section mapping), and mesh the 3D numerical computing grid. For its data format, the geological surface serves as the core, and the irregular triangular net surface serves as the main means. A closed surface is usually used to express the stratum/fracture zones, dikes, alteration zones, and other entities; a single plane is used to express fault and structural planes, and a circular plane can be utilized to express single structural planes.
In an underground water-sealed storage cavern project, hydrogeological data, such as the underground water level, water-conducting fractures of rock mass, and permeability zoning, should be included in the 3D geological model. For a storage cavern project that measures more than 3 million m² wide, multiple engineering and hydrogeological units are usually involved, and the spatial cross relation between the cavern and the geological structure is especially complex. Hence, the guidance function of the 3D geological model design is particularly important.

2.2 Monitoring data of surrounding rock

The data on the deformation of surrounding rocks and the stress of the support structure in the construction and operation periods are used to evaluate the mechanical states and evolution trend of the surrounding rocks on a given site. The internal deformation of surrounding rocks, stress of rock bolts, water level or water pressure, microseismic data, and so on are included in common data projects. The locations of monitoring points and the monitoring data comprise the monitoring data content; the former is provided as 3D coordinates for all measurement points, and the latter is provided as the time series of the monitoring data.

2.3 Three-dimensional mechanical model

The 3D mechanical model serves as the data indicating the mechanical state of the surrounding rock mass. It includes the 3D calculation grid, material properties, boundary and load conditions, and calculation results. A list of the node coordinates of the 3D grid and the adjacency relations between elements make up the 3D computing grid. The material properties are the deformation and strength parameters of the constitutive model of rock mechanics, in addition to the parameters of the seepage mechanics model. For a storage cavern project, the parameters are usually the Mohr–Coulomb model and the permeability coefficient of rock mass. The boundary and load conditions mainly include the excavation scheme, which is similar to the construction plan for the excavation of the cavern group.

3. Basic implementation method

The key to the implementation of the mechanical information model is to comprehensively utilize basic engineering data and effectively extract key mechanical parameters of rock mass. Subsequently, the 3D geological model and numerical calculation model of surrounding rocks can be refined. For the problem of insufficient geological data/information for in situ design, the method of geophysical data deduction based on field test data is adopted (Section 3.2).

3.1 Synthesis analysis of engineering information

As shown in Figure 2, a 3D geological model is established by integrating geological information, and a 3D numerical calculation model is then built by adding the mechanical information of geological bodies. Thereafter, the monitoring information, computational data, and other information can be integrated and stored in a unified 3D numerical model. Checking the validity of the mechanical model parameters requires the inversion analysis of the surrounding rocks of storage caverns based on monitoring data.
3.2 Extraction from geophysical and test data

The multielectrode electricity method is a common geophysical prospecting method that is used to output the distribution of the apparent resistivity of rock and soil and then analyze the qualitative information, such as the stratification and zoning of rock and soil and the occurrence of groundwater. According to the structure of rock mass and the principle of the multielectrode electricity method (Figure 3; for convenience, the figure shows two schematic joint sets in the fracture network), the apparent resistivity of rock mass is directly related to the amount of water in the fracture network; it is also related to the characteristics of groundwater seepage. Comparing the results with the data obtained by the water pressure test on boreholes shows the empirical quantitative relationship between apparent resistivity and permeability coefficient. Then, a large number of parameters representing rock properties can be proposed on the basis of the geophysical data (Figure 5). These parameters can then be used to calculate the stability of the 3D numerical model and evaluate the mechanical state of surrounding rocks.

Figure 2. Type of information synthesis

Figure 3. Testing principle of multielectrode electricity method

Figure 4. Data conversion of multielectrode electricity method
Figure 5. Regression analysis results between permeability coefficient of rock mass and its apparent resistivity

\[
\ln \left( \frac{1}{K} \right) = A \frac{\rho}{10000} + B
\]

\[
K = e^{-(A \frac{\rho}{10000} - B)}
\]

In equations 1 and 2, K is the permeability coefficient, \( \rho \) is the apparent resistivity, and A and B are two site-related fitting coefficients.

3.3 Comprehensive evaluation of rock mechanics

3.3.1 Evaluation of stability of surrounding rocks

In a previous stability evaluation of the surrounding rocks of a large-scale cavern, deformation monitoring analysis was employed as the main method on site, and a strength criterion was the main method used in the numerical calculation. Experience in cavern engineering reveals that the collapse of surrounding rocks is a combination of the deformation trend and failure surface. The specific calculation formula can be divided into the following two parts:

\[
G_r = \frac{1}{2} \left[ \frac{U}{U_{max}} + \max \left( \frac{\tau}{\sigma \tan \phi + c}, \frac{\sigma}{f_t} \right) \right]
\]

In equation 3, \( \frac{U}{U_{max}} \) is the deformation of the surrounding rock; \( \sigma \) and \( \tau \) are the normal stress and shear stress on the failure surface of the rock mass, respectively; \( c \) and \( \phi \) are the cohesion and internal friction angle of the rock mass; and \( f_t \) is the tensile strength of the rock mass.

1) Relative deformation: the ratio of the deformation of the rock mass to the maximum critical deformation around the cavern surface.

The greater the value of the relative deformation is, the closer the rock mass is to the instability state. According to the experience in water-sealed storage caverns, the maximum critical deformation around a cavern’s profile (measuring more than 18 m wide and 25 m high) can be estimated on the basis of the values shown in Table 1.

| Table 1. Estimated critical values for the maximum deformation of surrounding rocks |
|------------------------------------------|-----------------|-----------------|-----------------|-----------------|
| Q                                        | >100            | 10–100          | 1–10            | 0.1–1           | 0.01–0.1        |
| Umax (mm)                                | 30              | 60              | 80              | 100             | 120             |

2) Stress–strength ratio: the ratio of stress to the strength of the rock mass.

The ratio of shear stress to strength limit is adopted according to the typical Mohr–coulomb constitutive model in rock mechanics. The critical value of the stress intensity ratio is 1; it is greater than or equal to 1 when the rock mass enters the plastic damage state.

The stability of the surrounding rock can be determined by 1) and 2).

If the index is \( G_r < 1 \), then the surrounding rock mass is stable;

If the index \( G_r = 1 \), then the surrounding rock is in the critical state.

In the region where \( G_r > 1 \), the deformation and destruction of the rock mass are in critical state; hence, the region can be considered as unstable.
3.3.2 Evaluation of water seal effectiveness
The monitored water level (or pressure) and water inflow\textsuperscript{[15][16]} are conventionally used to evaluate the performance of the water seal, but other intuitive indicators are needed in the numerical calculation model.

To evaluate whether the seepage pressure in the seepage field of the rock mass meets the sealing requirement, we take the difference between 1 and the saturation $S_r$ of the rock mass as the evaluation index for water seal effectiveness.

$$G_w = 1 - S_r$$

When $G_w = 0$, the fractures of the rock mass are full of water.
When $G_w = 1$, the water in the rock fractures is completely lost, and leaking occurs.
When $0 < G_w < 1$, the fractures of the rock mass are unsaturated.

The area of the rock mass where $G_r = 1$ is completely dehydrated; it can be considered as the failure area of the water seal.

4. Engineering cases of underground water-sealed storage caverns

In view of the long-term nature and complexity in engineering practice of storage caverns, two practical excavation engineering cases are introduced in this work. The first one, which is detailed in Sections 4.1 and 4.2.1, is a project in a previous period to verify the basic technical route. The second one, which is detailed in Sections 4.2.2 and 4.3, is a comprehensive mechanical evaluation in an actual construction period.

4.1 3D geological model for underground water-sealed storage caverns

4.1.1 Engineering geological model
The topographic contour of a storage cavern project is shown in Figure 6. The overall terrain of the site is dendritic, with one corner being higher and with the diagonal corner being lower. The 3D model of the ground surface and the main faults and fracture zones is shown in Figure 7. We note two fracture zones and five faults. The main internal geological structure is shown in Figure 8(a). The typical geological section along the cavern axis is shown in Figure 8(b). The size of the model in Section 4.1 is approximately 3,000 m × 2,000 m × 400 m.

From the 3D geological model, the spatial relationship between the cavern group and the fracture plane is clear at a glance. Hence, we can clearly establish whether the plane and vertical layout of the cavern group is reasonable. This aspect can be accurately described by selecting different directions for cutting geological sections and geological bodies for the cutting intersection operation, which can be further used in the construction of numerical computing grids.

\textbf{Figure 6.} Topographic contour

\textbf{Figure 7.} 3D model of faults, fracture zones, and ground surface
4.1.2 Hydrogeological model
In the hydrogeological model, faults, fracture zones, other geological elements, and the impact of lithology interface should be considered. The relationship between faults, fracture zones, and lithology interfaces for a typical storage cavern is shown in Figure 9. The relationship between the ground water level and the geological boundary and the cavern group is shown in Figure 10.

4.1.3 Typical cavern group model
A typical cavern group model is shown in Figure 11. The model comprises 9 main caverns (measuring approximately 1,100 m long on average), 2 access tunnels, 9 water curtain tunnels, 6 process shafts, and 3 ventilation shafts; the designed total storage capacity exceeds 4 million m$^3$. The vertical relationship between the cavern and the shaft is shown in Figure 11. The water curtain tunnels are located above the cavern, and the process shaft head is lower than the ventilation shaft to minimize the head of the submersible oil/water pump.
4.2 3D mechanical model for underground water-sealed storage caverns

4.2.1 3D computing grid
A 3D calculation grid of the whole cavern group is shown in Figure 13; it comprises more than 1.5 million elements. The cavern group has multiple intersecting nodes, and mutual interference is inevitable in the excavation effect. The permeability coefficient distribution based on the geophysical data is shown in Figure 14 with significant heterogeneity in space.

4.2.2 Numerical calculation result
The 3D numerical calculation result for a typical main cavern excavation is shown in Figure 15. The figure shows the deformation situation around the cavern after the excavation of the top slice, along with the monitoring data of the multipoint extensometer serving as the source data of the inversion calculation [14]. An obvious imbalance is noted between the left and right spandrels of the cavern. Hence, the stress of the surrounding rock mass and corresponding supporting strengths of the two parts are different.
Figure 15. Calculation result of surrounding rock stability of cavern group in storage cavern

4.3 Application of comprehensive evaluation

4.3.1 Evaluation of stability of surrounding rock of cavern group
The evaluation result of the surrounding rock stability of the cavern group during the construction period of the storage cavern is shown in Figure 16. The stability states across the main caverns obviously differ. The figure also shows different changes along the axis direction.

Figure 16. Typical stability evaluation for surrounding rock of storage cavern

4.3.2 Evaluation of water seal effectiveness
The typical exploratory evaluation of the water seal effect of storage caverns is shown in Figure 17. An unsaturated seepage zone is formed in the loose zone of the surrounding rock because of the increase in the permeability coefficient after blasting. Moreover, a wide extension of the unsaturated zone is observed in the oval section of the cavern. However, because the unsaturated zone is not connected to the outside atmosphere, the reliability of the whole storage cavern is not affected.

Figure 17. Evaluation result of water seal effectiveness of typical storage cavern
5. Conclusion and discussion
With the proposed conceptual design, derivation, and case study, several conclusions can be drawn:
(1) The 3D geological model is crucial to the design of large underground water-sealed storage caverns. With the digital model of geological bodies and interfaces, the layout plan of cavern groups can be checked accurately, and the numerical model for the stability and seepage field of surrounding rocks can be established.
(2) The mechanical information model can be built by integrating various engineering information in a 3D numerical calculation model for storage cavern projects. The model can be used to guide the design and construction of storage caverns through mechanical state evaluation.
(3) A simple evaluation criterion of water seal effectiveness is proposed from the perspective of rock mass saturation. The criterion has a clear physical concept and can be easily obtained from calculation results.
Therefore, the proposed technical method for design optimization is basically feasible and can be gradually improved in future engineering practice involving large underground water-sealed storage caverns.

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