Research on Structure Characteristics of Surrounding Rock of a Large Underground Oil Storage in Rock Cavern

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Abstract. A series of analyses have been carried out based on geological data uncovered during the investigation and construction of the large underground oil storage in rock cavern, including the geological causes of the joints, structure characteristics of the surrounding rock, and the correlation between rock mass structure and quality. As a result, some significant understandings and practical conclusions were obtained. First, the investigation’s standard technical methods: geophysical exploration and drilling, are effective and applicable in revealing the engineering area’s large-scale structure. In the cavern, however, it is challenging to fully represent the structural characteristics of the surrounding rock. As a result, it is recommended that the adit survey method be used to improve precision and accuracy during the investigation period. Secondly, the existence of noticeable differences in the structural characteristics of granite from different locations is confirmed due to the influence of geological background. Therefore, the statistical distribution of joints based on data collected from a location far from the cavern may not accurately reflect the structural characteristics of the cavern’s surrounding rock mass. Finally, the closer the joints are to the ground surface, the more densely distributed they are and the more complex their geological characteristics become. As a result, the water curtains and main caverns should be designed with similar hydrogeological conditions and buried depths. Finally, because cavern engineering prioritizes hydrogeological characteristics such as surrounding rock permeability, joints with good engineering geological characteristics, such as the dense fracture zone, should be prioritized during the investigation and construction phases. This study gives the typical characteristics of large-scale faults, secondary faults, main permeable structures, secondary structural planes, and other structures of different levels in the survey and construction periods. In addition, the analysis and research methods of various discontinuities are summarized, which can serve as a reference for the subsequent similar cavern engineering practice.

Keywords: Underground oil storage in rock cavern; Structural characteristics of surrounding rock; Geological origin; Cavern investigation; Cavern design; Cavern construction

1. Overview
The National Fourteenth Five-Year Plan clearly states that the construction of oil and gas storage facilities should be accelerated [1]. Underground water-sealed caverns are excavated in underground rock masses and are arranged below the groundwater level. The seepage pressure of underground water into the caverns resists the leakage pressure of oil and gas in the caverns, thereby achieving the purpose of storage [2]. Compared with traditional ground storage, underground water-sealed caverns have significant advantages in safety, economy, and environmental protection and have gradually become the main form of oil and gas storage construction [3]. Although water-sealed caverns have been studied and practiced in China for many years, as an imported technology, many vital technical problems still need to be resolved [4]. The stability of the surrounding rock and the water sealability of the cavern are the two critical technical problems [5]. Large-scale water-sealed
caverns in China are mainly constructed in granite, with a buried depth of about 100 m and low geo stress. The stability of the surrounding rock of the caverns is generally reasonable. However, large-scale water-sealed caverns are cut by the structural and excavation surfaces and always presents local block instability problems [6]. The permeability coefficient of intact granite is small, only in the order of $10^{-7}$ m/d, while the permeability coefficient of the structural surface of the granite can reach the order of $10^2$–$10^3$ m/d [6]. Both the permeability characteristics and water sealing conditions of the caverns depend on the surrounding rock joints [7]. Therefore, in cavern engineering, it is essential to study the joints’ development characteristics and development laws.

Existing rock joint identification and information collection methods [8-11], joint development characteristics [12-14], fracture surface morphology description technologies [15-18], and other rock mass structure researching methods are widely used in cavern engineering. The rock structure three-dimensional display system, BIM technology, etc., have also been applied in some caverns [19, 20]. New technologies such as nuclear magnetic resonance have also been employed in cavern engineering [21]. In addition to drilling and geophysical exploration, the two caverns in Japan, Kuji and Kushikino, also used the adit survey method. Kuji excavated 640 m surveying adit, Kushikino excavated 430 m adit [22]. Hidekazu Yoshida et al. studied the development characteristic of joints in the largest LPG (Liquefied Natural Gas) reservoir in Japan (Kurashiki), and pointed out that the development characteristic of joints of Kurashiki reservoir is universal in Japan [23]. Li Zhongkui and others pointed out that because auxiliary caverns such as construction tunnels and water curtains are generally constructed earlier than the main cavern, the structural information exposed by the auxiliary caverns can provide a valuable reference for predicting the main cavern [24].

Comparing the current status of research on rock mass structure of water-sealed caverns, there is still a gap between domestic and global research on cavern engineering survey methods and joint development rules. Based on the geological information revealed during the survey period and construction period of a large-scale water-sealed cavern project in China, this study investigates the structural characteristics of the surrounding rock of the cavern from the perspective of the geological origin of the structural plane summarizes the typical characteristics of different types of joints and generalizes the cavern rock structure research methods, and corresponding suggestions are put forward to provide a reference for the similar type engineering.

2. The basic situation of the cavern
The researching cavern is located on the southeast coast of China. It is a crude oil storage depot with designed storage capacity of 5 million cubic meters. The underground engineering of the cavern includes 3 construction tunnels, 10 main caverns, 17 shafts, and eight water curtains. The structure of the underground cavern is shown in Figure 1. The underground project of the cavern began construction in January 2016 and ended in July 2020. The cavern has been sealed and has oil storage conditions.
The project area is a wavy plain and coastal zone, with denuded and remnant hilly landforms, little topography, with surface elevations between 0 and 32 m. The surface mainly exposes Quaternary residual slope deposits, and the underlying bedrock is especially Yanshan I-stage gneissic granite, intercalated with various types of lamprophyre veins, granite pegmatite veins, felsic veins, etc. The elevation of the bottom of the bedrock weakly weathered zone is −20 to −40 m. The typical geological section of the cavern project area is shown in Figure 2.

3. Analysis of regional geological conditions and joint formation

The project is located in the active belt of the continental margin of the southeast coast of China. Under the tectonic background of the Philippine plate squeezing the Eurasian plate to the NW, the basement faults of the area are mainly in the NE direction. The basement fault invaded the gneissic granites in this area along the NE direction in the early Yanshan period, and the magmatic rocks formed in the same period were distributed in a string of beads along the NE direction in the region. Since the granite formation, it has continued to undergo NW-direction structural compression, and at the same time, affected by the right strike-slip of the NE-directed basement fault, multi-stage structural fractures have been generated in the granite. Surveying, mapping, and statistics of the structural surfaces on the surrounding quarry and other outcropping surfaces during the engineering phase revealed that the ground surface around the project primarily developed three
groups of steeply inclined joints near EW, NW, and NS, with the near EW and NW-direction joints being relatively densely developed, as shown in Figure 3.

Figure 3 Joint pole isodensity map of surface mapping

4. Main control structure features
During the survey phase, it was determined that the engineering area has three faults: the F1 fault that strikes near EW, the fault F2 that strikes NW, and the fault F3 that strikes NE, using surface surveying and mapping, geophysical testing, borehole testing, and regional geological data analysis. Figure 4 depicts the distribution of F1, F2, and F3.

Figure 4 Shape of main control structure in the project

F1 is a regional fault with an occurrence of about $10^\circ \angle 75^\circ$. F1 is connected with the East River and is a water-conducting structure. F1 forms the main hydraulic boundary on the north side of the cavern. Figure 5 is the photo of the core of the ZK73 borehole crossing F1. The depth between 10 m and 75 m are fault fracture zones.
F2 obliquely penetrates the entire cavern from northwest to southeast, with an occurrence of about $230^\circ \angle 70^\circ$, and intermittent quartz veins can be seen on the surface along with F2. The results of geophysical prospecting showed that F2 was abnormally significant on the east and west sides and not evident in the middle, and it was presumed to be distributed in a geese pattern. Shallow seismic and high-density resistivity geophysical prospecting revealed that the shape of F2 on the 1-1’ section is shown in Figure 6 and Figure 7, and the position of the 1-1’ section is shown in Figure 4.

F3 obliquely penetrates the southeast corner of the cave from southwest to northeast, with an occurrence of about $145^\circ \angle 75^\circ$, where intermittent quartz veins were also observed on the surface. Drilling holes passing through F3 show that the rock mass at the fault zone is partially broken, and the pegmatite veins are exposed in multiple drilling holes. Therefore, it is inferred that F3 is a late pegmatite vein intrusion filling. The typical photos of the core drilled through F3 are shown in Figure 8 and Figure 9, and the corresponding drilling position is shown in Figure 4.

F1, F2, and F3 are smaller in scale, and the engineering properties are different. The location and characteristics of the F2 and F3 faults revealed by the drilling exploration and geophysical prospecting in the early stage are in good agreement with the fault morphology revealed by the excavation and showed that the existing survey methods are effective and applicable for revealing the large-scale structure of the cavern project.

5. Main permeable structures
In addition to the three faults (F1, F2, F3) revealed during the exploration stage, drilling and geophysical testing also showed that there are nine joint dense zones (J1~J9) and five altered fracture zones (P1~P5) in the cavern engineering area, as shown in rose-red in Figure 10. During the excavation of underground caverns, the joint dense zones and altered fracture zones revealed are permeable to varying degrees during the investigation stage. However, the structures revealed by cavern excavation are more than presented above. During the construction period, the geological catalog compiled 28 small faults (Class III structural planes, numbered f1 ~ f28) and 68 long joints and dense joints (Class IV structural planes, numbered L1 ~ L68), as shown in red in Figure 10. These structural locations have varying degrees of water permeability.

![Figure 10](image)

**Figure.10** Main permeable structures revealed in the investigation and construction period

The difference between the interpretation results of the permeable structure during the survey phase and the construction phase indicates that with the deepening of engineering practice, the disclosure of the permeable structure in the engineering area will gradually become clear. However, it also shows that the existing survey methods in the survey phase are not sufficient to fully reveal the rock’s actual permeable location and permeable characteristics.

According to the permeable joints exposed during the construction stage, the Class III joints (f) and the Class IV joints (L) are respectively counted, and their respective pole isodensity maps are drawn, as shown in Figure 11.

![Figure 11](image)

**Figure.11** Pole isodensity map of the permeable structure exposed during construction

the Class III joints are mostly steeply inclined, with inclination angles between 65° and 85°, and the direction is mainly in the NEE and NNW directions, and the NEE direction is the most developed. The on-site compilation results show that most Class III joints are not extended long but always altered. Steep inclination angles dominate class IV joints, and a small amount are gentle inclination angles. The inclination
angles are generally between 40° and 85°. The dominant direction is generally consistent with that of Class III joints. The trend is mainly NEE and NNW. Some Class IV joints have corrosion.

Comparing Figure 11 and Figure 3, the development law of the surface joint is not consistent with the joint exposed by the excavation of the underground cavern. The two groups of dominant joints with the most noticeable surface development are EW direction, and NW direction, respectively, and the two groups of underground dominant structural planes are NEE and NNW. The above differences indicate that the structural planes in magmatic rocks are more messy and complicated than those in sedimentary rocks. The granite in the project area is Yanshanian intrusive rock with a limited formation range. After formation, the structural fissures formed under structural action also have the characteristics of stages and groupings, but because they are close to the surrounding basement faults and other large structures, the large surrounding structures and their activities will affect the development characteristics of structural surfaces in granite, leading to large differences in the rock mass structure of different parts of the granite. Figure 3 shows the surface structure surface, the collection part is not completely directly above the cavern, and the distance from the cavern varies from several hundred meters to several kilometers. Therefore, the characteristics of structural planes collected and obtained at a certain distance from the surface of the cavern may not completely represent the structural characteristics of the rock mass of the underground engineering part of the cavern.

6. Statistical characteristics of joints

There are many secondary joints in the surrounding rock of the caverns, in addition to the aforementioned main permeable structures identified based on hydrogeological and engineering geological characteristics. According to the classification, these joints generally belong to Class IV~V and have the characteristics of staging and grouping. The existence of these joints leads to anisotropic permeability of the surrounding rock of the cavern.

The ten main caverns layout in the direction of NE10° and the six water curtains in the direction of SE100° were respectively counted on the exposed joints, and the pole isodensity diagrams of the joints in each cavern were drawn, as shown in Figure 12 and Figure 13. At the same time, the statistical results of the surface line density of each cavern are given.

Figure 12 Pole isodensity diagram and linear density statistical results in joints of main caverns

Figure 13 Pole isodensity diagram and linear density statistical results of joints in water curtains
It can be seen from Figure 12 and Figure 13:

1. The main cavern mainly develops two sets of steeply inclined dominant joints, and their directions are NEE and NNW, respectively, which are consistent with the permeable structure of the main cavern. The shape of the main cavern’s dominant joints indicates that the main cavern’s axial arrangement at NE10° is reasonable. Furthermore, the axial direction of the main cavern and the two groups of dominant joints intersect at a large angle, which is beneficial to the stability of the surrounding rock of the cavern.

2. The joints of the main caverns on the east and west sides are relatively developed, and the joints of the main caverns 3, 4, 5, and 6 in the middle are relatively sparse. The development degree of the joints of each main cavern has a corresponding good relationship with the water permeability characteristics during the excavation of the main cavern.

3. The exposed joints of the water curtain are more disarray than the main cavern. Except for the water curtain one, where two dominant joints with NE and NNW directions are obviously developed, the other water curtains generally develop three groups or even more. The dominant joints in water curtains 2, 5, and 6 are also developed with mild to medium inclination structural planes. This shows that the closer to the surface, the more factors that affect the characteristics of joints in the rock mass, and the less obvious the dominant joints.

4. The joints in the south water curtain are denser than the north water curtain. Especially the No. 1 water curtain has the lowest structural surface density among all water curtains. This shows that although the No. 1 water curtain is closest to the F1 fault, the rock mass near the large fault is not prone to stress concentration during the process of tectonic creation and reformation of the fracture, resulting in a complete rock mass structure than other regions.

5. The surface line density of the water curtain structure is between 0.2 and 0.3 lines/m, and the surface line density of the main cavern structure is between 0.1 and 0.2 lines/m. Thus, the surface line density of the water curtain structure is greater than that of the main cavern. It shows that the closer to the surface, the more structural planes in the rock mass, which has a guiding significance for choosing the appropriate buried depth of the cavern.

7. Quality characteristics of the surrounding rock of the cavern
Based on the construction catalog data of the water curtain and the main cavern, the Q classification method [25] is used to classify the quality of the cavern surrounding rock. A summary of the quality classification results of each cavern’s surrounding rock is shown in Figure 14. The figure also shows the location of the F2 and F3 faults and the main permeable structures exposed by the excavation.
It can be seen from Figure 14:

(1) The quality of the rock mass and the permeable structure have a corresponding good relationship. The locations of the rock mass with poor quality are also the locations where the permeable structure develops.

(2) Rock masses passing through faults F2 and F3 are generally of poor quality. Although geophysical prospecting revealed abnormalities in the F2 and F3 faults during the investigation stage, drilling revealed no obvious faults and only local core fragmentation or dyke filling. There was no evidence of large-scale faults, such as obvious mud-in-fractured zones, when the caverns were excavated to the F2 and F3 faults. The F2 and F3 faults mostly appeared as densely packed fissure ridges. The F2 and F3 faults have no significant impact on the stability of the cavern's surrounding rock from engineering geological characteristics. However, in terms of hydrogeological characteristics, the exposed parts of the F2 and F3 faults generally have strong water permeability and large water seepage. The amount of seepage is difficult to control, and the F2 and F3 faults also significantly impact the water seal conditions of the cavern project. The structural properties of rock mass represented by faults F2 and F3 are universal in cavern engineering and reflect the special requirements of cavern engineering for rock mass structure research.

8. Conclusions and suggestions
The stability of the surrounding rock and the water sealability of the cavern are two key technical issues in the underground engineering of the water-sealed cavern. Both are primarily influenced by the distribution and development of joints in the surrounding rock. The geological origin of the
surrounding rock structure, the structural features of the rock mass revealed during the investigation stage and the construction period, and the corresponding relationship between the rock mass structure and the quality of the rock mass, etc., were investigated in a large-scale water-sealed cavern project in China. And the following main conclusions and understandings are obtained:

(1) The large-scale water-sealed cavern projects in China are mainly located in the southeast coastal area, with similar geological conditions and structural background, and the rock mass structural characteristics of each large-scale water-sealed cavern project are also comparable. From the perspective of geomechanics, analyzing the genetic mechanism and development law of joints in the surrounding rock of caverns and the hydrogeological and engineering geological characteristics of various types of joints will help deepen the overall understanding of the surrounding rock structure of water-sealed caverns in China.

(2) Now commonly used geophysical prospecting, drilling, and other cavern engineering survey methods are effective and applicable to revealing the large-scale structure of the engineering area, but it is difficult to fully represent the structural characteristics of the cavern surrounding rock. The actual excavation reveals more rock mass structures than those found in the previous survey, which brings great unpredictability and uncontrollability to the cavern engineering design and construction. It is recommended that the adit survey method be introduced to improve the accuracy of cavern engineering investigation, based on the practical experience of foreign cavern engineering and domestic hydropower engineering, and other industry experiences. Through the excavation of the surveying adit during the investigation, the prospectors can enter the adit and conduct a detailed investigation on the development rules and characteristics of different levels of structural planes in the rock mass, thereby providing the detailed basis for subsequent engineering design.

(3) The domestic cavern projects are mainly located in the granite area where the Yanshanian intrusive diagenesis occurs. Although the joints in the rock mass also have the characteristics of stages and groupings, the distribution and development of the joints are not as consistent as the sedimentary rock regions. After the granite where the cave project is located intrudes along the basement faults, the morphology and activity characteristics of the large surrounding structures such as the basement faults will affect the development characteristics of the joints in the granite, leading to large differences in the rock mass structure of different parts of the granite. During the engineering survey of caverns, the characteristics of joints collected and obtained at a certain distance from the surface of the cavern may not completely represent the structural characteristics of the rock mass of the cavern.

(4) In the cavern engineering area, the closer to the surface, the more the number and the more complex the shape of the joints. In this cavern engineering example, the surface density of the exposed structure of the water curtain is about twice the surface density of the main cavern. As a result, the permeability of the surrounding rock of the water curtain will be significantly different from that of the main cavern, which will greatly increase the difficulty of predicting, analyzing, evaluating and controlling the hydrogeological conditions of the cavern engineering. Therefore, it is recommended that when designing the cavern depth in the subsequent cavern engineering practice, the water curtain tunnel and the main cavern should be arranged to the depth of similar hydrogeological characteristics.

(5) The engineering geological characteristics of structures that significantly impact the construction of caverns are not necessarily very poor. For example, the F2 and F3 faults in this cavern engineering mainly manifest as dense cracks and structural planes developed along the fault belt. Although there have been alteration problems, the scale of a single structural plane is not large, and the large structural features such as mud inclusion, fragmentation, and mylonitization are not obvious. However, the exposed parts of the F2 and F3 faults generally have strong rock mass permeability and hard to control, which significantly impact the construction of the cavern’s water sealing conditions. Therefore, large-scale fissure-intensive zones like the F2 fault and F3 fault will not significantly impact the stability of the cavern surrounding rock. Nevertheless, it is still the focus of the preliminary investigation and later construction treatment also reflects the particularity of structural research of water-sealed caverns.
(6) According to this cavern engineering example, the typical characteristics of large-scale faults, secondary faults, main permeable structures, secondary structural planes, and other structures of different levels in the survey period and the construction period are given, and the characteristics of different types of structural planes are summarized. Analysis and research methods can be used as a reference for similar engineering research and practice in the future.

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