The Principle, Evolution and Key Technical Problems of Large Underground Water-sealed Storage Caverns for Oil/Gas

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Abstract. The basic principle, structure, and characteristic of large-scale underground water-sealed storage caverns is introduced in the paper. Then its brief development history is summarized to three stages. On this basis, the key technical problems which is faced by such projects are explained combined with engineering experience. Finally, several characteristics of the technology are summarized, and some conclusions can be used as reference for colleagues in related research fields.

Key words: Hydrodynamic containment method; underground water-sealed storage caverns; fractured rock mass; groundwater level;

1. Introduction

Since the second industrial-technological revolution in the 1870s, with the successful development of the chemical industry and increased energy demand, petroleum and its derivatives have gradually become one of the lifeblood of the national economy. In the 21st century, despite the impact of a variety of new energy sources, global oil consumption accounts for 1/3 [1][9] (the largest proportion) of all sources, and its mainstream use for energy and chemical raw materials is still hard to be shaken. Therefore, the storage facilities of oil and its derivatives will be essential to stabilize the international market price in the future. As one of the critical storage methods, large underground water-sealed energy storage has the characteristics of low cost, high security, land saving, etc., and developed rapidly, especially in Asia, in the past two or three decades.

2. The basic working principle, structure, and characteristics

In general, there are several types of underground energy storage, such as depleted oil/gas reservoir, salt rock, and cavern storage, and underground cavern storage has relatively fewer requirements for geological conditions. Whether in igneous, metamorphic, or sedimentary rocks, cavern storage can be built as long as the rock block is hard, the rock mass is relatively whole, and there is no significant seepage channel. Among them, the underground water-sealed energy storage is an essential type of underground unlined cavern storage (URC) [2][174-181][3][4], which makes full use of the tightness of rock mass to store oil/gas without steel shell. When the underground unlined cavern storage is located
in the shallow rock stratum, the groundwater flow is always used to enhance the containment effect, which is the underground water-sealed storage caverns.

2.1. The basic working principle
The water-sealed storage caverns store oil/gas in the fractured rock mass using the hydrodynamic containment method [3][5]. With the formation of a stable seepage field in the surrounding rock, the flow direction of groundwater can be directed into the cavern to prevent oil/gas from leaking through the crack network. The control mode of water level in the water cushion below the oil products can be divided into variable water bed and fixed water bed methods. At present, the fixed water bed method with a water curtain system is the most common. The basic working principle is shown in Figure 1. It is suitable for storing crude oil and products at normal pressure and temperature and petroleum gas or natural gas at high pressure and normal temperature. The general control principle [5][9] of the underground water-sealed storage caverns can be simplified as equation (1). It is shown that the pressure difference between the lowest groundwater level and the roof of the storage caverns should not be less than the operating pressure in the gas phase space.

\[ P_w = P_g + S_f + S \] (1)

In this equation, \( P_w \) is the lowest groundwater level; \( P_g \) is the gas pressure, which is the operating pressure of the storage medium. \( S_f \) is the shape coefficient, which considers the change of water level caused by the distribution of the seepage field. \( S \) is the safety factor of water level fluctuations.

2.2. The basic structure
According to the references [10][11] and engineering experience, the basic structure of underground water-sealed storage caverns is as follows:

2.2.1 The main cavern
The main cavern is the central part of the storage volume, with the largest section size of about 15–20 m wide and 20–35 m high. When it is for storing crude and refined oil, the main cavern is usually used in the gateway-like structure, primarily to accelerate the construction schedule in relatively good geological conditions. In contrast, a horseshoe section should store gas media such as petroleum gas to prevent high operating pressure. The spacing of the main caverns is determined by the stability analysis of the surrounding rock of the caverns group, with the net distance about 1.5–2 times the width of the cavern according to engineering experience.
2.2.2 The process shaft and operating tunnel

The process shaft is the vertical channel for the transportation of oil/gas stored in the main caverns, usually from the ground through the main cavern down to the pump pit. It is mainly used in laying process pipelines and hoisting the equipment in the pump pit and should be sealed with reinforced concrete when the construction is completed. It will be filled with water for sealing to a certain height above the sealing plug; only sleeves are left for hoisting the equipment and sensors. While the size of the process shaft should satisfy the process installation requirements, it is also necessary to consider the convenience of construction operation that the diameter should not be too small. Furthermore, when the shaft outlet cannot be exposed to the ground due to the buried depth of the mountain, it is also necessary to set up the operating tunnel for daily operation, in which permanent ventilation, lighting, and escape measures should be considered.

2.2.3 The water curtain system

The water curtain system is the facility for injecting water into rock mass to control the dewatering funnel. It consists of the water curtain tunnel and water curtain boreholes. The boreholes in the water curtain system are geological drilling holes for water injection to the surrounding rock of main caverns. They are also used as advanced geological exploration holes before the construction of the main caverns. After completing the boreholes, several water pressure tests should be carried out to test the surrounding rock's local and overall seepage characteristics. Generally, horizontal boreholes are arranged above the caverns for oil storage caverns, while vertical boreholes are placed on the boundary for storage caverns, with the radial boreholes arranged in a local position. The water curtain tunnels are the necessary channel for constructing the boreholes and will be filled with water to submerge all boreholes after the construction until the design water level in the surrounding rock is reached.

2.2.4 The access tunnel

The access tunnel is the traffic channel for accessing the main caverns and water curtain tunnel, drawn from the ground entrance, circulated and reciprocated underground, connected to the main cavern and water curtain tunnel. It is the main traffic channel for personnel transportation and slag transportation and the essential ventilation channel in the construction period. Therefore, the slope of this tunnel should meet the maximum slope requirement of the vehicle, and the section size should meet the needs of the construction equipment and the ventilation line, with the height and width generally between 8–10 m. After completion of underground construction, a sealing plug-in connection path near the main cavern should be set up to prevent the possibility of oil spillover through the access tunnel. At the same time, the entrance of the access tunnel should be blocked, and water should be filled for sealing between it and the sealing plug.

2.2.5 The ventilation shaft

This is the shaft used to ensure the ventilation effect for excavation of main caverns in the construction period. The size of the section should satisfy the requirements of ventilation calculation, which is usually the main vertical channel of the forced ventilation. From an economic perspective, the ventilation shaft should be less arranged in principle and avoid connecting directly with the main cavern. After completion of the underground construction, the intersections of the ventilation shaft and cavern group should be filled with concrete in time.

An independent storage unit is formed by several connected main caverns, which is called an underground tank. A large underground water-sealed storage is made up of several underground tanks. The three-dimensional model of a typical underground tank is shown in Figure 2.
2.3. The main characteristics

2.3.1 Safety
The underground water-sealed storage caverns are located at a certain depth below the surface, so it has a natural advantage against earthquakes. The structural seismic design is not needed for the storage caverns in principle. Here, there is no overflow space in the storage caverns with basically no fire protection requirements. It is generally built in relatively complete rock masses; its resistance to war and natural disasters is much stronger than the storage tanks on the ground.

2.3.2 Economy
The underground water-sealed storage caverns are an unlined cavern project. The geological conditions have been optimized in the preliminary investigation process so that the cost of excavation and support of the cavern group is relatively low. In the later stage of the construction, all underground passageways should be closed to form a permanent project with a design period of no less than 50 years. The main anti-corrosion measures are cathodic protection and corrosion allowance. Construction measures can also control the water inflow in the cavern; thus, operation and maintenance costs are lower than storage tanks on the ground. Generally, when the capacity of a single tank is more than $10^4$ cubic meters, the construction cost of an underground water-sealed cavern is less than the traditional ground storage tanks. The larger the capacity and the larger the gap, the more significant difference is, and the maximum can save about 20%. According to the statistics [11], its operating cost can be controlled at about 1/6 of the ground storage tank.

2.3.3 Land saving
The vertical position of the oil reservoir in underground water-sealed storage caverns is located at a certain depth, and it has no influence on the ground structure from the view of stress. In principle, the surface space above the storage caverns can be used as relevant industrial or civil facilities, as long as the groundwater level is not affected by the protection of the groundwater level in the reservoir area when the safety protection distance to the oil and gas facilities in the process shaft area is met. For Wang Hua chemicals in Yantai, an underground storage cavern for LPG under its factory units, with normally operating for several years, has achieved good economic benefits. In 2005, underground storage for oil products about 280000 cubic meters of limestone [15], which had been built to solve the
relocation problem caused by the occupation of old oil tanks in urban areas in Greece, has achieved considerable economic benefits.

3. The evolution history

The underground water-sealed energy storage originated from the Nordic country, Sweden, was born out of the underground concrete tank technology for oil storage during World War II. Then the unlined underground oil storage was completed in Sweden, and the artificial water curtain system was adopted later. This technology was developed in Europe and expanded to the rest of the world with the progress of the global economy.

3.1. The trial stage (from the 1940s to the 1970s) [10][12][16][18]

In 1939, the concept of storing oil in the unlined cavern below groundwater level was first put forward by Jansson in Sweden, based on the oil storage practice of underground concrete tanks. In 1948, after the Second World War, the first underground unlined storage caverns were built from a feldspar pit in Sweden. It was used for heavy oil storage. In 1950, the first underground unlined storage caverns for gas (LPG: liquefied petroleum gas) was built in a shale formation site in the United States. In 1959, the first underground unlined storage caverns for oil, based on fixed water cushion, was built in Sweden, and then five storage caverns were built later in 1967. Subsequently, the unlined storage caverns were applied in other European countries. For example, in France, limestone ore caverns were converted into LPG reserves in 1967, and disused iron ore was built to oil storage caverns with a storage capacity of 5 million m³ in 1973.

In this stage, the prototype of underground water-sealed storage caverns was developed using a variable water level method in mine transformation. Then the fixed water bed method had begun to appear in the underground unlined storage caverns. The artificial water curtain system was first used in underground storage for LPG to ensure the reliability of the water-sealing effect.

3.2. The application stage (from the 1970s to the 1990s) [17][20][21]

In the 1970s, after experiencing two oil crises, underground oil reserves were constructed in industrialized countries such as Europe, the United States, Japan, and South Korea. In the United States, reservoirs in the underground salt cave with a capacity of about 120 million cubic meters had built based on its geological characteristics. In Norwegian, its first storage cavern for crude oil with a water curtain system in granodiorite was built in 1976, and water-sealed storage caverns for LPG with the capacity of 0.10 million m³ were built one year later. In South Korea, the underground oil storage named U-2 with the capacity of 4.30 million m³ was built in 1985, expanded twice from 1990 to 1997 and from 2002 to 2006, with a total capacity of 7 million m³. Then, the underground oil storage named U-1 with the capacity of 4.45 million m³ was built in andesite and tuff in 1998, underground storage for oil products was built with a capacity of 0.23 million m³ in the granite in 1982, and its capacity was expanded to 0.39 million m³ in 1994. The LPG (propane and butane) underground storage with a capacity of 0.29 million m³ in South Korea was built in the limestone and tuff in 1983, and five underground storage caverns for LPG was successively built in gneiss, sandstone, and siltstone form 1989–2000, with a total storage capacity of 2.0 million m³. In Japan, two underground storage caverns for crude oil, with a capacity of 1.75 million m³ and 1.50 million m³, was built in the granite from 1987 to 1993, and one underground storage cavern for crude oil with a capacity of 1.75 million m³ was built in andesite rock at the same time.

In the 1970s, the study and practice for construction of underground oil facility have begun in China. In 1977, the first underground storage caverns for crude oil were built in Shandong province; it has a total volume of 0.15 million m³ and is under the natural groundwater level. Then several underground storage caverns were also constructed for crude oil. In the 1980s, an underground storage cavern for oil products with a 4000 m³ was completed in Zhejiang province. However, underground oil storage was not further developed during this period due to China’s change of war readiness demand.
Finally, in 1999, the LPG storage caverns with a capacity of 0.20 million m$^3$ were completed in Shantou in Guangdong province, and it is the first underground commercial gas storage in China.

During this stage, crude oil storage in water-sealed energy storage had increased rapidly, and the maximum storage capacity of a single tank had exceeded 4 million cubic meters. On the other hand, underground storage for LPG also had begun to prosper, but the storage capacity of a single storage tank is relatively small, generally no more than 0.5 million m$^3$. In addition to the United States, the basic technology of underground storage caverns was mainly the fixed water bed method with an artificial water curtain system.

3.3. The expansion stage (since the year 2000)
In the past two decades, the demand for oil resources has been expanded quickly with the change of the world economic pattern. As a result, the relevant technologies have spread worldwide, especially in emerging market countries. For example, around 2013, water-sealed storage caverns for oil with a volume of 1.74 million m$^3$ were built in Singapore [22], and oil storage caverns with a capacity of 1.50 million m$^3$ have been built in India. At the same time, several underground oil reservoirs with a level of million cubic meters were built in China. Meanwhile, the LPG underground reservoir is developed rapidly because of its rapid turnover and high profitability. In 2002, an LPG underground storage cavern with a capacity of half a million had been built in Ningbo. In 2015, an underground storage cavern with a capacity of one million cubic meters had been completed in Yantai. At present, an LPG storage cavern with a capacity of 2.0 million m$^3$ is being built in Ningbo in Zhejiang province.

In this period, the water-sealed storage caverns for crude oil have continued to grow rapidly, and the capacity of underground storage for LPG has begun to reach the level of one million cubic meters. As a result, the construction of large-scale water-sealed storage caverns is becoming prosperous all over the world.

4. Key technical problems
There are several following key technical problems involved in large-scale underground water-sealed storage caverns, in addition to conventional technical issues just as a large parallel dense cavern group.

4.1 The stability of surrounding rock during the construction period
The purpose of large underground water-sealed storage caverns is to store oil/gas, so in principle, there is no lining, and the bearing capacity of surrounding rock is utilized by shotcrete-bolt support. However, due to the selection of geological conditions in the preliminary survey and the selection of the spacing between oil storage caverns in the scheme design, the possibility of overall failure can be generally excluded. According to the relevant engineering practice experience, the local stability of the surrounding rock of a single cavern is the main problem in the construction period.

4.1.1. The locally stability of cavern in poor geological sections.
Because the large-scale underground water-sealed storage caverns occupy a relatively large area, it is difficult to avoid local poor geological sections such as small faults, fracture zones and weathering bursa even in the site with relatively complete geological conditions. Since the storage cavern has already exceeded the self-stability scale of surrounding rocks, it is necessary to strengthen support and reduce construction disturbance when the storage caverns pass through the poor geological sections. In addition, since the storage medium of storage caverns is gas or fluid, the key is to ensure the storage space and flow path. Therefore, the section size of storage caverns can be partially reduced to reduce the difficulty and cost of support.

4.1.2. The block stability of hidden weak discontinuity
In the construction period of underground caverns, advanced exploration is usually carried out on the heading face. But, if there is an undiscovered, large, inverted, and concealed weak discontinuity in the sidewall, it is enough to form a large wedge-shaped block combining with the high sidewall, which
can be extended to the arch shoulder. Here, improper disposal can significantly affect construction safety. In this way, advanced geological exploration means on the sidewall should be added. Then the supporting measures of the sidewall of the middle and lower layers should be strengthened and supported in time. Finally, when necessary, an oval section should be employed to increase the rock pressure around the cavern and enhance the block stability.

4.2 The stability of groundwater level

Changes in the groundwater level are encountered after the excavation of underground caverns. If the changes are not processed, the groundwater level will drop below the top of the storage caverns to form leaks. Therefore, keeping the groundwater level in a relatively stable state is the key to maintaining the tightness of underground water-sealed storage caverns. Therefore, necessary technical measures should be taken for the groundwater level changes during the construction period:

4.2.1 Dynamic monitoring of water level

To control the dewatering funnel caused by the excavation of the cavern group, after the construction of water curtain holes in the water curtain system is completed, clean water is injected into the rock mass through the water curtain boreholes. It is difficult to avoid the local groundwater level falling below the roof of the storage cavern. Therefore, in the construction process, the groundwater level monitoring network [23] is established through geological drilling to dynamically monitor the change in the groundwater level on the site. In the actual operation process, a drop in the water level of the monitoring boreholes below a certain height above the roof of storage caverns is taken as the primary standard for monitoring and controlling the groundwater level.

4.2.2 Search and processing of concentrated seepage channels

It is shown by numerical calculation and engineering experience that a concentrated seepage channel will cause a large drop in local groundwater level through the storage caverns. Therefore, the groundwater level distribution, water inflow in the caverns, the injection amount of water curtain boreholes, and other hydrogeological data should be integrated when the storage caverns encounter partial precipitation loss pressure. Then the approximate orientation of the concentrated seepage channel should be determined using tracing test methods, geophysical prospecting, or micro-seismic event analysis [24]. Finally, the grouting scheme should be arranged and implemented accordingly, and the construction can only continue when the groundwater level has been restored to the normal level.

4.2.3 Seepage field simulation of surrounding rock

One of the characteristics of an underground water-sealed energy storage project is to simulate the distribution of seepage fields in surrounding rock to evaluate the water-sealing effect [25]-[27]. The underground storage caverns are a complex three-dimensional cavern group, and the calculation of seepage field in surrounding rocks should be mainly based on numerical simulation. Its primary method is to adopt the stable seepage model in continuum seepage mechanics, with the value of seepage parameters from monitoring of water level, rock mechanics test, and statistical analysis, and take the coupling effect of seepage field and stress field [25] into consideration. In nearly a decade, the discrete element method in the discontinuous media seepage model has also been developed [8] to consider the heterogeneity and instability of the seepage field caused by joints and fissures. For underground storage caverns of LPG with high storage pressure, it is necessary to consider the unsaturated seepage model [9][20] or multiphase seepage theory [28] to calculate and evaluate the water-sealing effect.

5. Conclusions and prospects

Based on the descriptions above, several conclusions can be summarized as follows:
(1) The principle of the underground water-sealed storage caverns for oil/gas is clear, and its structure is simple. Without steel shells and reinforced concrete linings, the caverns can be conveniently constructed and operated.

(2) The key technical problems in constructing large underground water-sealed storage caverns are mainly during the construction period, which requires on-site disposal and dynamic design.

(3) Stability of groundwater level and seepage field is the key to containment performance, and relevant theoretical models and simulation methods need to be further improved.

With the development of the social economy and the evolution of international collaborations, the construction scale of reserve projects for oil/gas will continue to expand. Moreover, because of advantages in security and economy, large underground water-sealed storage caverns are bound to have a good development prospect in the future. Hence, they should be one of the hot research topics in rock mechanics and engineering.

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