Research Status and Prospects of Key Technologies for Underground Water-sealed Oil Storage Cave

DOU Ming-yuan\(^{1,2,3}\), ZOU Shuai\(^{1,2,3}\), LI Hao-ming\(^{1,2,3}\), FENG Qing\(^{1,2,3}\), HUANG Fu-chuan\(^{1,2,3}\) and LIAO Xiao-hua\(^*\)

\(^1\)College of Mechanical Engineering, Guangxi University, Nanning, Guangxi, 530004, China
\(^2\)Guangxi Key Laboratory of Petrochemical Resource Processing and Process Intensification Technology, Guangxi University, Nanning, Guangxi, 530004, China
\(^3\)Guangxi Key Laboratory of Processing for Non-Ferrous Metals and Featured Materials, Guangxi University, Nanning, Guangxi, 530004, China
\(^4\)South China branch of Sinopec Sales Co., Ltd

\(^*\)Corresponding author’s e-mail: 2422559717@qq.com
Author’s e-mail: doumingyuan@foxmail.com

Abstract. Petroleum is the lifeblood of the national economy. The underground water-sealed oil storage cave has become the main development direction and research object of petroleum reserve at home and abroad due to its advantages. This paper summarizes the research progress of key technologies for large-scale underground water-sealed oil storage cave, emphasizes the current role of underground water-sealed oil storage cave in petroleum reserve, and discusses water curtain system and water sealing, surrounding rock permeability and evaluation, surrounding rock stability and evaluation, field construction technology and related issues, and also emphasizes the importance of strategic petroleum reserve (SPR), and has prospects to the future development of underground water-sealed oil storage cave.

1. Introduction

Petroleum is called the blood of industry, is an important resource guarantee to guarantee national energy security and social and economic sustainable development, and plays an extremely important role in national defense construction and security. According to the data of the National Bureau of Statistics, China's oil output in 2018 was 189.1 million tons, and its oil import volume was 461.89 million tons, with an external dependence of 70.59%. According to the increase of China's oil demand, it is expected that China's total oil demand will exceed 700 million tons by 2020.

China's Strategic Petroleum Reserve Plan originated in 1973. Strategic petroleum reserve is one of the effective ways to cope with short-term oil supply. In the construction of petroleum reserve system, countries with suitable geological conditions tend to build underground oil storage caverns [1]. Compared with the above ground storage, the underground storage has the advantages of high security, long service life and can avoid the attack of conventional weapons [2]. As a kind of underground reservoir, water-sealed underground oil reservoir has the advantages of strong geographic adaptability, large inventory size, easy expansion and small footprint [1].
The theory of underground water-sealed reservoirs was first proposed by Hageman, father of rock mechanics and oil reserves in Sweden. Since the 1980s, the world has made great efforts to develop the underground water-sealed oil storage cave. For example, three underground oil storage caverns have been built in Japan, i.e. Kuji, Kikuma and Kushikino.

The development of underground water-sealed oil storage cave in China is relatively late. Since the 1970s, China has vigorously developed the technology of underground water-sealed oil reservoir, and built the first underground water-sealed cavern with a volume of $15 \times 10^4$ m$^3$ in Huangdao in 1973. In the second phase project of National Petroleum Reserve, half of the reserve base is underground water-sealed oil reservoir. With the arrival of the third phase project of the petroleum reserve, there is an increasing demand for the technical development of the underground water-sealed oil reservoir.

2. Water Curtain System and Water Sealing

The key to water sealing of underground water-sealed oil storage cave is whether there is a stable water cap layer above the cavern, and the thickness of the water cap layer is 5m, which is suitable [3]. However, due to the imperfection of the theory of water sealing conditions and the different geological conditions, the water pressure outside the cavern is often increased by setting artificial water curtain. Water curtain hole is the core component of water curtain system. At present, the layout of water curtain holes can be divided into three types: horizontal, vertical and inclined.

The design of water curtain system has always been the most important part of the design of underground water-sealed caverns. Liang Bin et al. [4] analyzed the groundwater seepage field and evaluated the water sealing effect of an underground water-sealed oil storage cave during its operation by using the method of modeling and analysis. It was found that the expansion rate of water level line under the condition of water curtain is smaller than that under the condition of no water curtain, indicating that the condition of no water curtain is easier to form a distinct drop funnel than that under the condition of water curtain. Peng Zhenhua et al. [5] discussed the situation of guaranteeing water sealing without artificial water curtain system, and gave the relevant conditions from groundwater conditions, the permeability of surrounding rock of cave and reservoir, etc.

At present, most of the water curtain systems of the oil reservoirs that have been built are mainly horizontal water curtain. Li Yutao et al. [6] used the finite element numerical simulation method to study the layout of the expansion cavern with and without vertical water curtain, and concluded that when the distance between the two caverns is small, setting vertical water curtain can reduce the impact of the proposed cavern on the cavern already built. Gao Bin et al. [7] deduced the calculation formula of equivalent permeability tensor, simulated the seepage flow field under the combination of different permeability tensors and different water curtain layout ways, and concluded that the arrangement way of curtain holes perpendicular to the main direction of permeation should be used.

Aberg.B. et al. [8] believe that the sealing of the cavern can be guaranteed as long as the vertical hydraulic gradient is greater than 1, while ignoring the influence of gravity, friction and capillary forces. However, the contradiction between the nature of the surrounding rock seepage of the cavern and the equivalent medium analysis method affects the design of the water seal system [9]. Therefore, there are not many pure theoretical studies on the water curtain system at present, most of which summarize the experience through engineering examples. Zhang Qihua [10] summarized and evaluated the project of Huangdao National Petroleum Reservoir and affirmed the supplementary role of artificial water curtain system in groundwater decline. Zhongkui Li et al. [11] used the first large water-sealed underground oil depot in China for reference, and discussed some design and operation problems related to water curtain system during the construction of the project. Large-scale water-sealed underground caverns have been put into use only in recent years. Relevant theories and experiences about water curtain water-seal system still need further study by experts and scholars.

3. Formatting the text Stability and Permeability of Surrounding Rock

During the construction of underground water-sealed cavern, due to the existence of weak structural planes such as cracks, interbeds, joints, etc., the surrounding rock mass is not uniform, anisotropic,
discontinuous and other defects, which will affect the site construction and the stability of the surrounding rock. Therefore, a large number of scholars have carried out a series of studies on the stability and permeability of the surrounding rock of underground oil storage caverns.

3.1. Stability of Surrounding Rock

The stability evaluation of surrounding rock has always been one of the most important problems in the cavern construction of underground water-sealed oil storage cave. Qi Lan [12] et al. discussed the stability of surrounding rocks of underground caverns based on the analysis of ground stress field. Zeng Haizhao et al. [13] analyzed the stability of surrounding rocks of a large underground tunnel based on block theory and UNWEDGE software, which provided a useful reference for underground construction. Yao Zhongtao [14] provides a quantitative index for the stability of surrounding rocks of underground caverns by means of finite element analysis based on catastrophe theory. B Zhang et al. [15] put forward a method combining experiment and numerical value to evaluate the stability of underground cavern in Anhui. The result shows that the cavern has good stability. Based on cloud theory and principal component analysis (PCA) method, Zhiqiang Li et al. [16] put forward a new analysis model for surrounding rocks of groundwater sealing chamber, which is of great significance to reduce risks during construction. Qingwen Ren et al. [17] put forward a comprehensive evaluation method of surrounding rock safety applicable to underground tunnel construction. This method can be used to evaluate the deformation stability of surrounding rock and quickly predict the collapse of rock mass, providing a new idea for the safety of surrounding rock in underground tunnel construction.

Due to the complex underground environment, many factors affect the stability of surrounding rocks. Su Feng [18] analyzed and summarized the influence of cylindrical jointed rock mass on stability of surrounding rocks of underground caverns. Liu Peng et al. [19] based on FLAC3D finite difference software, analyzed the influence of fault fracture zone and spacing between caverns on stability of underground water-sealed caverns. These have certain reference value for actual construction on site.

3.2. Permeability of Surrounding Rock

In order to achieve good water sealing effect, the underground cavern needs to construct below the groundwater level, so the seepage problem must be considered in the design of underground cavern [9]. For underground water-sealed reservoirs, the control of water seepage in caverns is the core of seepage analysis and seepage prevention treatment [20]. According to the current research level, the seepage models of jointed and fractured rock mass mainly include three kinds: equivalent continuum model, double-medium model and discrete fracture network model.

3.2.1. The equivalent continuum model. Equivalent continuum model regards rock mass as equivalent continuous medium, including rock block and fissure, without considering the anisotropy of medium, it is described by a comprehensive elastic modulus. The physical variables used are the average value of each field, and the problem of coupling seepage field and stress field in rock mass is studied by continuous mechanics method [21, 22]. Li Shucai et al. [23] took a large underground water-sealed oil cavern in China as the background, combined with field test data analysis, used the method of equivalent continuous medium, used anisotropic permeability tensor of fractured rock mass and established three-dimensional model to predict the change of underground water level in different construction stages. Lu Wenlong et al. [24] used GeoStudio software and equivalent fissured rock mass to continuous medium, discussed the influence of fractured zone on water inflow of cavern.

3.2.2. The double-medium model. The double-medium model (fracture-pore seepage model) [25] considers not only the flow of fluid in joints and fracture networks, but also the flow of fluid in rock blocks. Cui Shaodong et al. [26] established a dynamic water inflow calculation method based on the seepage model of rock mass pore and fissure dual media. Shao Jiansheng et al. [27] studied the law of velocity change, pressure distribution and the influence of different shapes of fissures during the
seepage process of double-medium model. Because the water exchange between fracture and pore is complex, the main cracks can be analyzed by this method in the actual analysis process, and the small cracks and rock blocks can be analyzed by using the equivalent medium model.

3.2.3. The discrete fracture network model. The discrete fracture network model [28] regards the rock mass medium as a fracture medium system, examines the flow of water in the fracture network and ignores the water conduction function of rock blocks. Based on the advantages of discrete fracture network, a large number of scholars and experts have used discrete fracture network model to simulate and analyze the water tightness and water curtain system of underground caverns combined with field engineering data in recent years [29, 30, 31, 32, 33].

4. On-Site Construction.
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4.1. Construction Risk Analysis
There is less experience in the construction of underground water-sealed oil storage cave in China, although there are corresponding design specifications [34], it is not mature. The construction of underground water-sealed cavern has the characteristics of long construction period, difficult construction, large investment amount, immature technology, poor experience and many uncertain factors. There are certain safety risks in the construction process. Therefore, the safety risk assessment during the construction period is of great significance. Wang Zhechao et al. [35] carried out safety risk assessment of the cavern during construction from two aspects of stability and sealing of the cavern. Guo Shunli et al. [36] evaluated the construction risk of underground water-sealed oil storage cave relying on Huangdao underground water-sealed oil reservoir, analyzed and summarized the evaluation method and control theory of construction risk. Ke Chao [37] analyzed the risk of underground cavern construction based on Fuzzy mutation theory. The construction analysis and analysis of underground water-sealed cavern can not only ensure the safety of construction objects, but also enable the smooth implementation of the project as planned.

4.2. Construction Technology
4.2.1. Excavation blasting technology. The excavation blasting of underground water-sealed oil storage cave has the characteristics of complex construction environment, high requirements for forming effect, large blasting vibration and strict damage control. Li Peng et al. [38] optimized the blasting method for excavation of large underground water sealed cavern. He Guofu et al. [39], Fu LuKun et al. [40], Zhi Wei et al. [41], Sun Haijiang [42], Zou Can [43] combined with the actual blasting engineering test of underground water-sealed cavern, analyzed and summarized the experience of relevant vibration detection and blasting control, which has certain reference value for the blasting design and construction of large underground water-sealed cavern. Now, there is a kind of double roll drilling and blasting free construction technology applied to the excavation construction of underground water-sealed oil storage cave, which greatly promotes the construction efficiency, environmental protection and safety.

4.2.2. Shotcrete technology. Jet concrete layer is the key supporting layer of large underground water-sealed oil storage cave, and its performance has a significant impact on the construction of oil depot and the later operation and maintenance. Wang Jun [44] studied the high performance shotcrete of large underground water-sealed cavern, and analyzed the mix ratio, working performance and mechanical properties of concrete. Qin Zhiyong et al. [45] analyzed the bearing characteristics of
anchor shotcrete support structure, discussed the working status of shotcrete and surrounding rock, which has certain guiding significance for future underground cavern construction.

4.2.3. Other Technologies. Large underground water-sealed oil storage cave has the characteristics of long construction period, high construction conditions and complex construction environment, so more and more technical processes are used in underground water-sealed oil storage cave. Wang Ke [46] studied the application of three-dimensional laser scanning in underground caverns and proposed a new method for measuring the volume of large underground water-sealed oil storage cave. In recent years, the widespread use of Beidou navigation system has brought great convenience to the initial mapping and design of underground water-sealed oil storage cave. In addition, combined with the means of big data, the spatial positioning in the early stage of the project is more accurate, the project is safer and more standardized during construction.

5. Conclusion and Prospect
(1) Underground water-sealed oil storage cave has many advantages, such as large scale of stock, relatively small investment cost and small area. Therefore, large-scale construction of underground water-sealed oil storage cave is the key development direction of China's strategic petroleum reserve.

(2) The construction of underground water-sealed oil storage cave in China is relatively late, and the technology and experience are immature compared with developed countries. In the later work, we need to strengthen the research on these theoretical basis.

(3) At present, the standards for construction of underground water-sealed oil storage cave are not perfect, and many technical standards are derived from field experience or standards of other relevant industries. However, with the development of the national strategic petroleum reserve system, relevant standards will be constantly revised and improved.

(4) At present, the employees of underground water-sealed caverns are relatively concentrated. The existing relevant units and personnel may not be enough to undertake the construction and research of underground water-sealed oil storage cave. Therefore, all practitioners and universities should strengthen the training of relevant professionals.

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