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Theoretical and Technological Challenges of Deep Underground Energy Storage in China

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ABSTRACT

Deep underground energy storage is the use of deep underground spaces for large-scale energy storage, which is an important way to provide a stable supply of clean energy, enable a strategic petroleum reserve, and promote the peak shaving of natural gas. Rock salt formations are ideal geological media for large-scale energy storage, and China is rich in salt rock resources and has a major shortage of energy storage space. Compared with the salt domes in other countries, the salt rock formations in China are typical lacustrine bedded salt rocks characterized by thin beds, high impurity content, and many interlayers. The development of large-scale energy storage in such salt formations presents scientific and technical challenges, including: ① developing a multiscale progressive failure and characterization method for the rock mass around an energy storage cavern, considering the effects of multifield and multiphase coupling; ② understanding the leakage evolution of large-scale deep underground energy storage caverns; ③ understanding the long-term performance evolution of large-scale deep underground energy storage caverns; ④ developing intelligent construction technologies for the deep underground salt caverns used for energy storage; and ⑤ ensuring the long-term function of deep underground energy storage spaces. The solution to these key scientific and technological problems lies in establishing a theoretical and technical foundation for the development of large-scale deep underground energy storage in China.

1. Introduction

China must urgently transition to low-carbon energy consumption in order to meet the challenges of global warming. At the General Debate of the 75th Session of the United Nations General Assembly in 2020, President Xi Jinping announced on behalf of the Chinese government that China will strive to peak its carbon dioxide (CO_2) emissions before 2030 and to achieve carbon neutrality before 2060 [1]. Since 2017, the Chinese government has gradually intensified its policies to promote low-carbon energy, and a comprehensive energy supply system of coal, electricity, oil, natural gas, and renewable energy has been formed [2]. Fig. 1 presents the major energy consumption and CO_2 emission reduction in China from 2015 to 2019, and shows that coal is still the major energy source for China, although its proportion is gradually decreasing [3]. The proportion of clean energy, which consists of natural gas and non-fossil energy, has increased significantly. For example, the proportion of clean energy increased from 17.9% in 2015 to 23.3% in 2019. Meanwhile, the proportion of non-fossil energy (wind, solar, geothermal, and hydro, etc.) increased from 11% in 2015 to 15.3% in 2019. Fig. 1 also indicates that CO_2 emission reduction in China has greatly increased and has a positive relation with increasing non-fossil energy consumption. At present and in the future, China's main goals are to adjust its energy consumption structure and to increase the proportion of clean energy in order to counter CO_2 emissions.

Accelerating the use of non-fossil clean energy is the general trend of global energy consumption and China's priority in the nation's energy development. By the end of 2019, the global total installed capacity of renewable energy reached 2.537×10^9 kW. It now accounts for 34.7% of the total installed capacity of electricity—an increase of 1.4% compared with 2018—of which the installed capacity of wind and solar energy contributes about 72% [3]. In 2019, 15.3% of China's energy was provided by wind and solar energy. The total installed capacity of wind- and solar-derived energy in China reached 2.42×10^8 kW. During the 13th Five-Year Plan, the average annual growth rate of installed capacity

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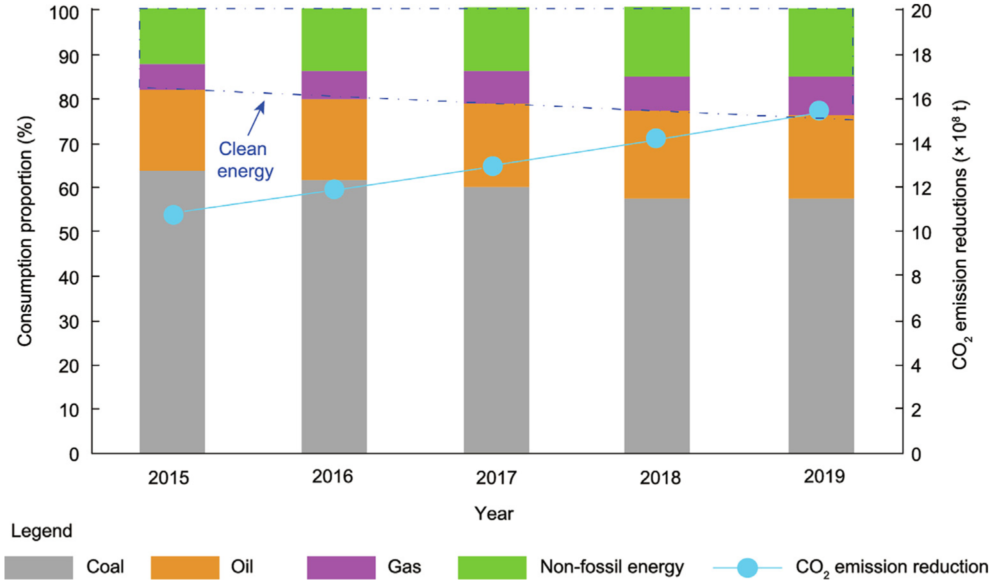

Fig. 1. Consumption of major forms of energy and CO_2 emission reduction in China from 2015 to 2019 [3].

of wind- and solar-derived energy was about 12% [3]. Because wind energy and solar energy have typical regional characteristics and cannot be supplied continuously and stably, their use brings a series of challenges to the stable operation of the power grid and restricts the rapid development of renewable clean energy. Fig. 2 displays the abandoned wind and solar energy in China from 2015 to 2019 [3]. Abandoned wind and solar energy is defined as the power generated by wind and solar exceeding the sum of the maximum transmission and load consumption of power. Abandoned wind and solar energy reached a maximum in 2016 and then decreased gradually, but its total amount is still relatively large. For example, the total abandoned wind and solar energy in 2019 was about 2.15×10^{10} kW·h, which is equivalent to 22% of the Three Gorges power generation (i.e., the largest power station in the world) in the same year [3]. To improve the utilization efficiency of renewable energy, it is essential to quickly establish large-scale energy storage facilities, including pumped-hydro energy storage, compressed air energy storage (CAES), liquid flow batteries, and hydrogen storage [4]. Pumped-hydro energy storage needs a specific geological structure to realize conversions between potential energy and electric energy [5]. CAES uses the surplus electric energy generated by renewable energy to compress air into large underground spaces, and then uses the compressed air (or adds natural gas for supplementary combustion) to drive steam turbines to generate electricity at peak hours. This method can achieve a continuous and stable supply of renewable energy [6]. Liquid flow batteries use battery packs to convert abundant electric energy into chemical energy for storage. Limited by their environmental and other costs, liquid flow batteries can provide limited-scale energy storage at present [7]. There are also relevant experimental reports on liquid flow battery energy storage using deep salt caverns [8], which provides an idea for large-scale energy storage using liquid flow batteries.

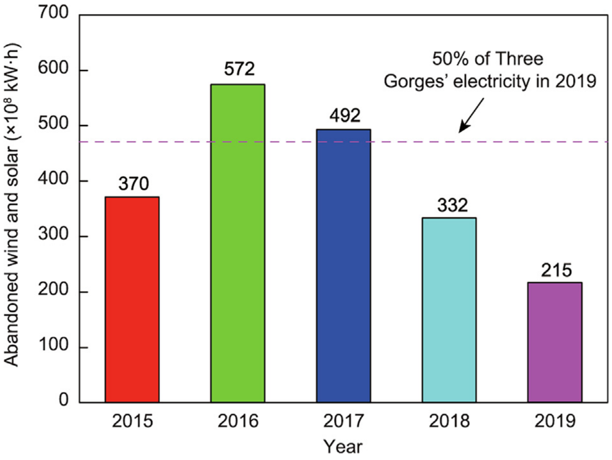

Fig. 2. Amount of abandoned wind and solar energy in China from 2015 to 2019 [3].

Hydrogen energy is one of the main goals of clean energy development and is the most effective way to attain the sustainable development of energy. The governments of various countries are actively encouraging the hydrogen energy industry, based on different development backgrounds [9]. In comparison with other energy sources, hydrogen energy has the following four advantages:

(1) **Wide sources.** Hydrogen can be obtained from coal, petroleum, and water—especially by the electrolysis of water (or seawater), which does not produce pollutants.

(2) **High calorific value.** The amount of heat released by burning 1 kg of hydrogen is 4.87 times that of coal and 3.94 times that of natural gas.

(3) **Free of pollution.** Hydrogen burns to produce water (H_2O), which is environmentally friendly.

(4) **Rich application scenarios.** Hydrogen energy can be widely used in automobiles, aerospace, power generation, and so forth. It is also used as a chemical raw material.

In 1970, the United States first proposed the concept of the "hydrogen economy." The Obama administration later issued the Comprehensive Energy Strategy, and the Trump administration made hydrogen and fuel cells a priority of the US energy development strategy [10]. In October 2003, Japan proposed a "hydrogen society" for the first time in its First Energy Basic Plan [11]. In 2019, Japan released the newly revised Hydrogen Fuel Cell Strategic Roadmap, raising the utilization of hydrogen to a national strategic level [12]. China included "promoting the construction of charging and hydrogenation facilities" for the first time in its 2019 government work report, clarifying China's development plan and layout for hydrogen energy production, storage, transportation, and refueling [13]. According to the White Paper on China's Hydrogen Energy and Fuel Cell Industry, China's demand for hydrogen will account for 5% of its terminal energy consumption in 2030, with an annual demand of 35 Mt. In 2050, hydrogen energy will account for 10% of China's terminal energy consumption, with an annual demand of 60 Mt [14]. Hydrogen has a smaller molecular weight than natural gas, so hydrogen storage requires more space and a better sealed storage space than natural gas storage. Taking 35 Mt as an example, about 1.3×10^8 m^3 of storage space is required when the gas pressure is 30 MPa, which presents challenges for the large-scale utilization of hydrogen energy. Hydrogen storage in deep underground salt caverns has been tested abroad [15] and provides a new means of large-scale hydrogen energy storage.

As so-called "industrial blood," petroleum plays an important role in the world's energy consumption. In the 1990s, China changed from a net oil exporter to a net oil importer, and its oil imports have maintained fast growth. In 2019, China's petroleum consumption reached 714 Mt, of which 514 Mt were imported, and its external oil dependence reached 72%. China's petroleum import channels mainly include offshore, northeast, northwest, and southwest channels. Offshore channels are the main import source of petroleum, accounting for about 70% of China's total import petroleum. Petroleum is not only industrial blood but also a strategic material, whose supply is strongly influenced by the international political and economic environment. Therefore, the International Energy Agency (IEA) recommends the petroleum reserves of its member countries to cover no less than 90 days of their consumption to ensure the security of their petroleum supply [16]. China's strategic petroleum reserve (SPR) started late and is mainly stored on the ground surface. Compared with using deep underground spaces (i.e., salt caverns) to store oil, surface storage tanks have the following disadvantages:

(1) **Poor economy.** According to the experience of the United States, the cost of storing one barrel (1 barrel = 158.98 L) of crude oil in a ground surface storage tank is about 15–18 USD, in a hard rock cavern is about 30 USD, and in a deep salt cavern is about 1.5 USD [17].

(2) **Poor security.** Oil is inflammable and explosive, so fire and other risks for ground surface tanks are high. Examples include the Huangdao oil depot fire in 1989 in China [18] and the ground oil tank fire in Chiba in Japan, induced by the earthquake in 2011 [19]. Surface oil storage tanks may also be the main targets of military strikes and terrorist attacks. For example, the surface oil storage tanks of Aramco were attacked by cruise missiles on 24 November 2020 [20].

(3) **Occupies a large area.** Taking the construction of an oil storage farm with 5 Mt of surface oil storage tanks as an example, about 1.3×10^6 m^2 of land is needed, and personnel-intensive production and activities cannot be carried out within a certain distance from the oil storage farm.

As a clean energy source, natural gas has good economy and is environmentally friendly. Thus, natural gas is a good transitional energy to replace oil and coal. Since the implementation of the Gasification of China initiative in 2017, natural gas consumption in China has shown explosive growth [21]. In 2019, China's natural gas consumption reached 3.067×10^{11} m^3 [22], 1.345×10^{11} m^3 of which was imported natural gas, accounting for 43.8%. China's natural gas import channels mainly include the northwest, northeast, southeast, and southwest channels [23]. Long-distance pipelines are the main transportation mode. The southeast channel is dominated by maritime liquefied natural gas (LNG).

The main production areas of natural gas in China are in the southwest and northwest, while the main consumption areas are in the central and eastern regions. The main production and consumption areas are connected by a long-distance pipeline network. Gas consumption is highly variable within a typical season, day, or even hour. Large-scale storage of natural gas is the key to ensure the steady supply of natural gas. At present, China's large-scale natural gas storage facilities mainly include depleted reservoirs, salt caverns, and LNG storage tanks. According to international practice, it is only once the storage of working gas reaches about 15% of annual consumption that a safe supply of natural gas can be ensured [24]. China's natural gas storage facilities seriously lag behind the development needs of the natural gas industry, which has repeatedly led to large-scale gas shortages [25]. In 2018, the *Guidance on Energy Work* issued by the China National Energy Administration clearly pointed out that 3.5×10^{10} m^3 of effective working gas will be placed in underground gas storage, and a natural gas reserve system will be established by 2030 [26]. In 2020, the National Development and Reform Commission of China issued the *Implementation Opinions on Accelerating the Construction of Natural Gas Storage Capacity*, which pointed out that China's lagging gas storage infrastructure construction and insufficient storage capacity have become prominent problems restricting the safe and stable supply of natural gas and the healthy development of industry [27]. Therefore, accelerating the construction of underground gas storage is an important strategic demand to ensure China's energy security.

Based on the above analysis, the use of deep underground spaces for large-scale energy storage is one of the main methods for energy storage. In particular, energy storage in salt rock formation is the mainstream way [4,28,29] and is urgently needed for China's energy structure upgrading and transformation and energy security. In this paper, we analyze the current status of petroleum, natural gas, compressed air, liquid flow battery, and hydrogen energy reserves in deep underground spaces and predict their development trends. Three key scientific problems and two technical problems in the construction of deep underground energy storage are summarized according to the geological characteristics of bedded rock salt formations and China's energy storage requirements. Research and breakthroughs in these key scientific and technical problems can provide basic theoretical and technical guidance for large-scale energy storage in rock salt formations in China.

2. Types and status of deep underground energy storage

2.1. Petroleum

Oil storage methods predominantly include ground storage tanks, salt caverns, and hard rock caverns, among which salt cavern storage is the most common method. The US SPRs include Bryan Mound, Big Hill, West Hackberry, and Bayou Choctaw, with a total of 60 salt caverns and a cumulative oil storage capacity of 713 million barrels [30]. These SPRs not only guarantee the energy security of the United States but also establish the dominance of the United States in the pricing of international oil.

Germany's oil reserves include petroleum, gasoline, diesel, and heavy oil. Its petroleum—about 73 million barrels—is mainly stored in underground salt caverns [31]. France's SPR currently stands at 184 million barrels, which is equivalent to 85 days of the country's consumption. The French SPRs consist of an underground salt cavern and above-ground oil tank depots. China's SPR was mainly stored in the surface storage tank depots, and using the underground spaces for SPR is planned [32].

2.2. Natural gas

Storing natural gas in deep underground spaces, including depleted oil and gas reservoirs, salt caverns, aquifers, and abandoned mines, is a common method. Fig. 3 presents the types of global gas storages constructed in deep underground spaces and their key parameters as of the end of 2018 [33]. There are 662 deep underground gas storage facilities globally, with a total working gas volume of 4.21×10^{11} m^3. Salt caverns account for 15% of the total gas storage amounts, 8% of the working gas storage, and 26% of the peak-shaving capacity [33]. The rapid peak-shaving capability of salt cavern gas storage has strong applicability to the increasingly flexible natural gas market supply, and more and more countries and regions have implemented this storage method.

By the end of 2019, China had built 25 gas storages with a working gas capacity of about 1.5×10^{10} m^3, including 22 depleted reservoir gas storages and three salt cavern gas storages. The working gas of these underground gas storages accounts for about 5% of the country's natural gas consumption, which is still far below the 15% consumption required to ensure China's safe gas supply. However, the regional distribution of gas storage in China is strong. Central and Eastern China are two of the most economically developed regions in China, with a strong demand for natural gas. These areas lack the geological structures commonly for gas storage, such as depleted reservoirs and aquifers, but are rich in salt resources. Major salt mines in these areas include Jintan and Huai'an in Jiangsu Province, Qianjiang and Yunying in Hubei Province, and Pingdingshan in Henan Province. At present, more than 40 salt caverns with a total working gas capacity of more than 1×10^9 m^3 have been completed. They are operated by the companies PipeChina, Sinopec, and Ganghua Gas Storage.

2.3. Compressed air

Clean energy, such as wind, solar, and tide energy, has typical regional characteristics and the natural disadvantage of an interrupted supply. Large-scale energy storage is the key to improving the efficient utilization of clean energy. Fig. 4 presents a schematic diagram of a CAES power station [6]. CAES converts the surplus electric energy generated by clean energy into potential energy through compressed air and releases the potential energy to convert it into electric energy at peak usage time, thereby balancing the power grid supply.

Due to the low energy density of compressed air, a large storage space is required to achieve large-scale energy storage. Deep underground spaces are ideal storage places, with the advantages of large volume and a high-pressure-bearing capacity [34,35]. At present, there are two CAES power stations in the world, both of which use deep salt caverns for compressed air storage [15]. The Huntorf salt cavern CAES power station in Germany began operation in 1978 and was the first CAES. Its designed peak load capacity is 290 MW for 2 h or 60 MW for 8 h [36]. The second CAES power station, located in McIntosh, AL, USA, was completed in 1991, with a designed peak load capacity of 110 MW for 26 h [36]. At present, the main means of power grid peak shaving in China is pumped-hydro energy storage. The construction of a CAES power station in China using a deep underground space is still in its infancy. Jintan CAES power station is the first energy storage project in China utilizing a salt cavern, with a capacity of 60 MW/300 MW·h in the first stage [37].

2.4. Hydrogen

Fig. 5 presents a schematic diagram of the production, supply, storage, and sale of hydrogen energy. The large-scale underground storage of hydrogen energy is an indispensable link in the whole hydrogen energy industry. At present, there are four hydrogen storages using salt caverns, including Teeside (1972) in the United Kingdom, and Clemens (1983), Moss Bluff (2007), and Spindletop (2017) in the United States [15,38]. The hydrogen stored in these salt caverns is primarily used as industrial feedstock and has not yet been used for energy storage and adjusting power peaks. Imperial Chemical Industries utilized three salt caverns for storing hydrogen in Teesside in 1972 [15]. In 1983, ConocoPhillips utilized a salt cavern with a volume of 580 000 m^3 in the Clemens Salt

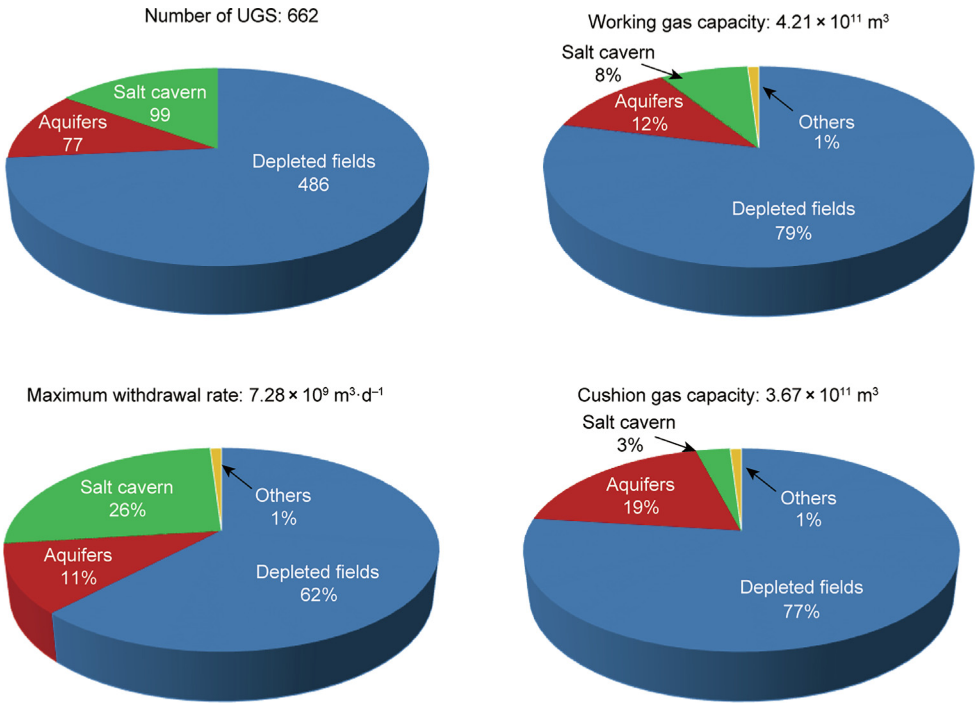

Fig. 3. Types of global gas storages constructed in deep underground spaces and their key capacities as of the end of 2018 [33]. UGS: underground gas storage.

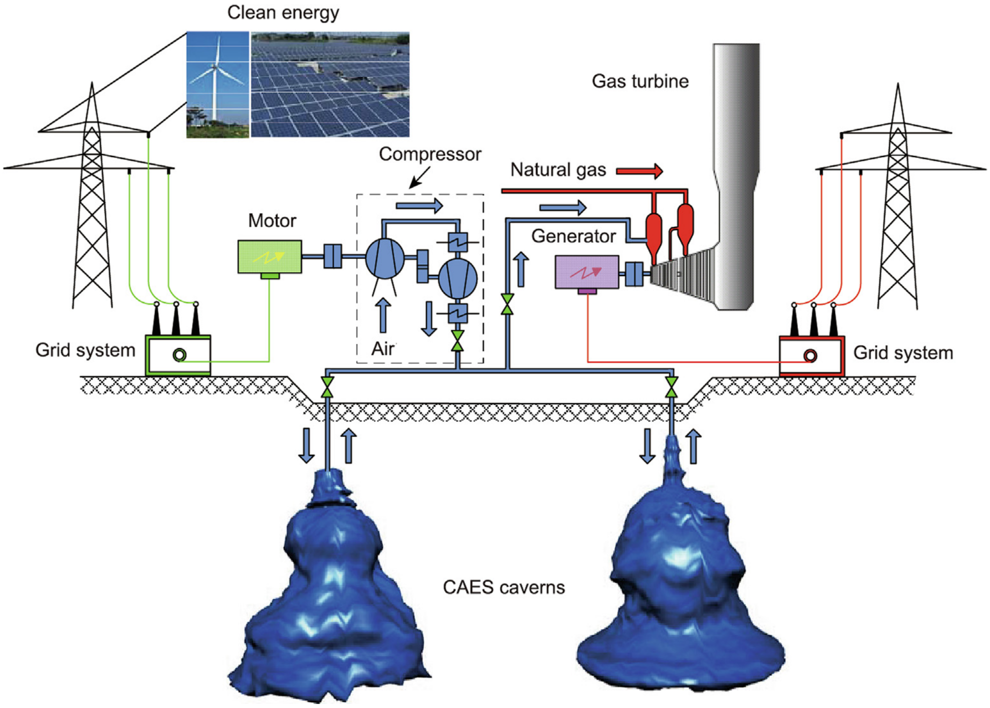

Fig. 4. Schematic diagram of a CAES power station. Reproduced from Ref. [6] with permission.

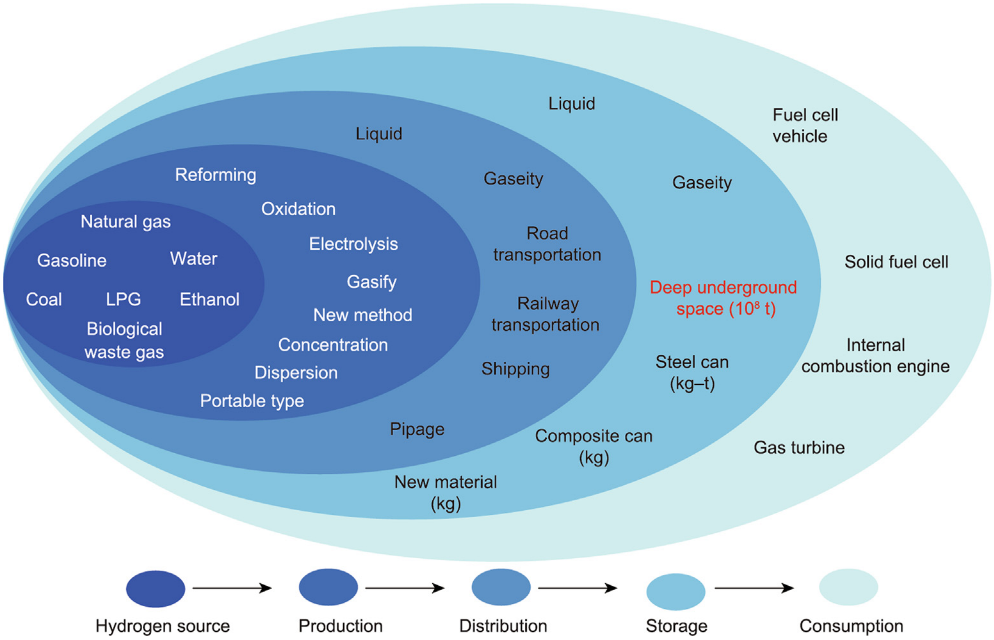

Fig. 5. Production, distribution, storage, and consumption of hydrogen energy. LPG: liquefied petroleum gas.

Dome in Texas for hydrogen storage [15]. In 2007, Praxair began the use of a salt cavern in Moss Bluff to store hydrogen for chemical plants in Texas and Louisiana. Although there are only a few cases of salt caverns being used for hydrogen storage, this method has huge advantages in terms of safety and economy. Many scholars have already carried out relevant studies [39–41], and the use of salt caverns for hydrogen storage will become the next research focus in the field of deep underground energy storage.

2.5. Liquid flow batteries

Liquid flow batteries are an electrochemical energy storage technology that was first proposed in 1974 [42]. They are a kind of high-performance battery in which positive and negative electrolytes separate and circulate separately [42]. Such batteries are characterized by a wide application field and long lifetime, but their energy density is low. Large-scale energy storage requires a considerable amount of storage space. In 2017, Ewe Gasspeicher GmbH, a German energy company, announced progress in building the world's largest liquid flow battery using underground salt caverns in northwest Germany as liquid storage tanks in order to achieve large-scale storage (Fig. 6) [43]. A system consisting of two medium-sized salt caverns can store enough electricity to power a large city, such as Berlin, for an hour. The battery is expected to be put into operation by the end of 2033. This provides a new idea for the resource utilization of deep underground spaces for energy storage.

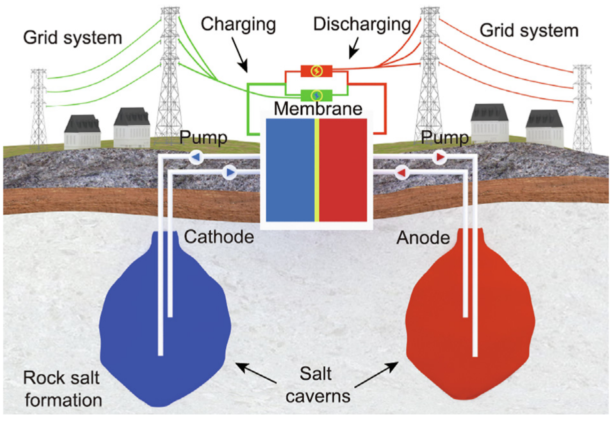

Fig. 6. Schematic diagram of a salt cavern flow battery.

3. Key theoretical and technical research challenges of deep underground energy storage

Compared with the salt domes abroad, salt rocks in China are typical lacustrine sedimentary bedded rock salt [44–47], and Chinese rock salt caverns thus have three disadvantages for energy storage. ① The rock salt formation is thin. The bedded rock salt in China is mainly lacustrine deposits with a thickness of less than 200 m, such as the Jintan salt mine in Jiangsu Province, the Heze salt mine in Shandong Province, and the Sanshui salt mine in Guangdong Province. As a result, the cavern volume is relatively small, generally around 200 000 m^3. In comparison, the height of salt domes abroad can reach more than 500 m, and the volume of a single salt cavern can reach hundreds of thousands or even millions of cubic meters [48,49]. ② The impurity content of the rock salt is high, and interlayers and rock salt appear alternately. The impurity content of rock salt in China is generally higher than 20% [29,50]. During cavern leaching, impurities and interlayers break and swell, and are then left at the bottom of the cavern. The volumes of these insoluble impurities and interlayers account for more than 40% of the cavern, causing the cavern leaching to have a low efficiency. At the same time, the high impurity content and the alternate appearance of interlayers results in a poor cavern shape and frequent accidents during cavern leaching using the water solution method. It also limits the leaching speed of the caverns. ③ Rock salt deposits generally occur in graben or semi-graben faulted basins. The rock salt formation in the middle of the salt basin is thick and gradually pinched around or separated by the basin boundary faults. A series of secondary faults are developed in the middle of the basin [44,51]. Moreover, different degrees of dislocation occur along these faults. In general, the middle area of the salt basin sinks, and the edge area uplifts. As a special geological structure, a fault has the characteristics of high permeability, large porosity, and low strength, and thus has no natural gas storage capacity. Rather, it is a potential leakage channel in deep salt caverns used for energy storage.

Fig. 7 presents five key scientific and technical problems presented by deep large salt caverns used for energy storage in China: ① developing a multiscale progressive failure and characterization method for the rock mass around an energy storage cavern, considering the effects of multifield and multiphase coupling; ② understanding the leakage evolution of large-scale deep underground energy storage caverns; ③ understanding the long-term performance evolution of large-scale deep underground energy storage caverns; ④ developing intelligent construction technologies for the deep underground salt caverns used for energy storage; and ⑤ ensuring the long-term function of deep underground energy storage spaces.

3.1. Developing a multiscale progressive failure and characterization method for the rock mass

When deep salt caverns are used for energy storage, the rock mass surrounding the salt caverns will be affected by many factors, such as chemical corrosion, temperature changes, and stress changes. Multiscale failure may occur, such as the establishment of nanoscale micro-fracture connectivity, meter-scale surrounding rock cracking, and kilometer-scale fault activation. The deterioration of the surrounding rock salt varies with time. Accurately describing the multiscale progressive failure of the surrounding rock mass under the conditions of multi-field and multiphase coupling is the basis for the storage medium determination, optimal design, and safe operation of deep salt cavern storages.

There are many types of energy storage media. The rocks surrounding salt caverns include salt rock, mudstone, and anhydrite. Under the high-temperature and high-pressure conditions during energy storage, the energy storage medium may react chemically with the surrounding rock, deteriorating its physical and mechanical properties. Available research [52,53] shows that the following chemical reactions may occur during the storage of crude oil in salt caverns:

$$\text{Hydrocarbon} + CaSO_4 \rightarrow CaCO_3 + H_2S + S + CO_2 + H_2O$$

$$2C_nH_{2n-1}COO^- + Ca^{2+} \rightarrow (C_nH_{2n-1}COO)_2Ca$$

These chemical reactions take place slowly and will not significantly weaken the surrounding rock mass. The $(C_nH_{2n-1}COO)_2Ca$ generated by the chemical reactions can partially block the pores in the surrounding rock mass, which is conducive to the tightness of the salt cavern storage.

When brine is used to replace oil and other storage media in salt cavern storage, the following chemical reaction may occur [52]:

$$MSiAlO_n + H^+(OH)^- \rightarrow M^+(OH)^- + [Si(OH)_{0-4}]_n + [Al(OH)_6]_n^{3-}$$

This reaction OH^- will lead to the expansion or even collapse of mudstone interlayers in the rock mass surrounding a cavern, which will significantly reduce the strength of the surrounding rock and increase its permeability.

Available studies show that hydrogen will react with minerals in the rock surrounding salt caverns under certain temperature and pressure conditions, which will increase the permeability and reduce the strength of the rock salt. At the same time, toxic H_2S is produced [39]. Therefore, the influence of chemical corrosion should be fully considered in the process of planning the use of a deep salt cavern to store energy.

The physical and mechanical properties of rock salt are sensitive to temperature and stress. Fig. 8 presents the effects of stress and temperature on the mechanical parameters of rock salt [54]. The Young's modulus of rock salt increases with an increase in

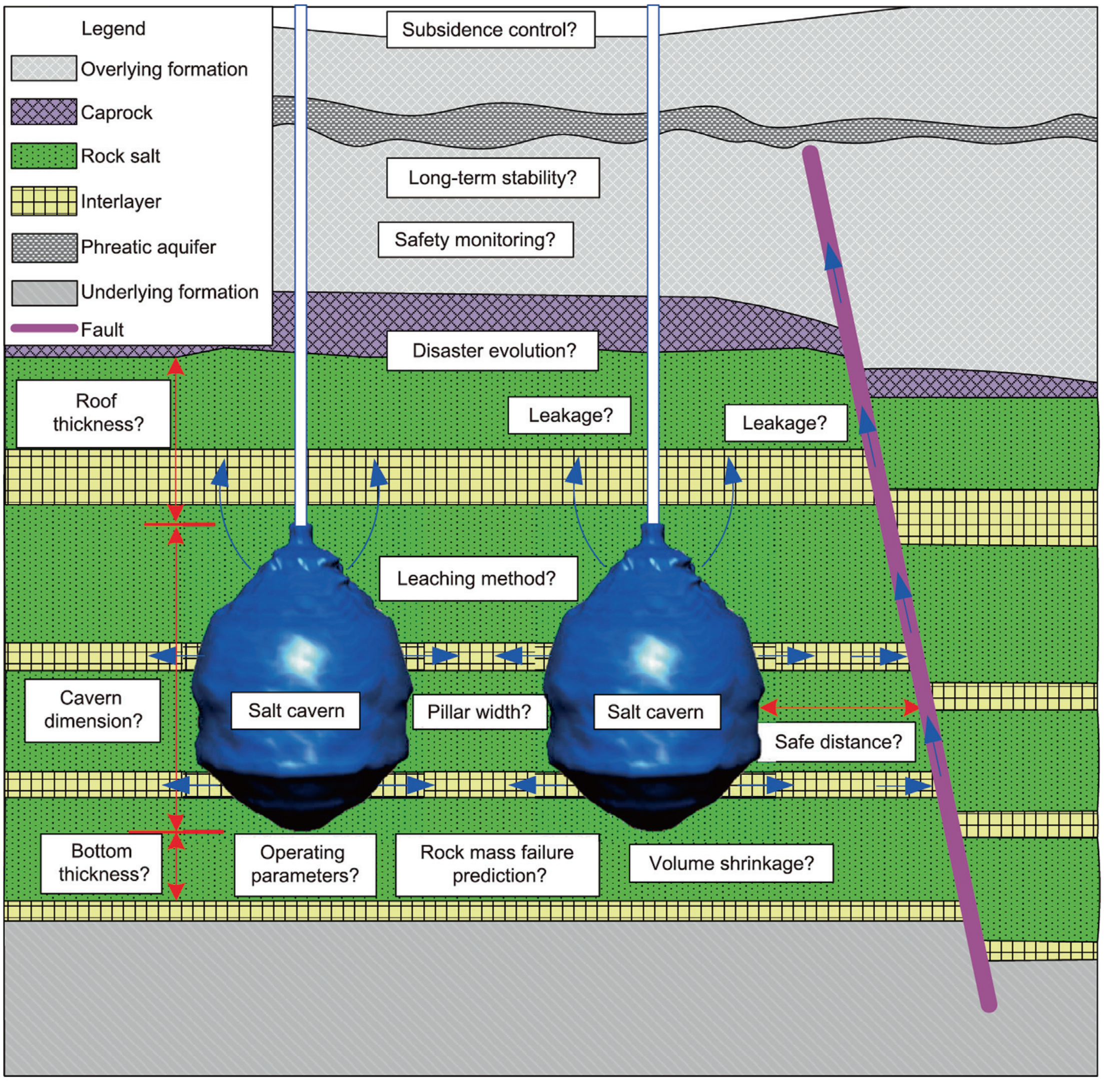

Fig. 7. Key scientific and technical problems presented by the deep large salt caverns used for energy storage in China.

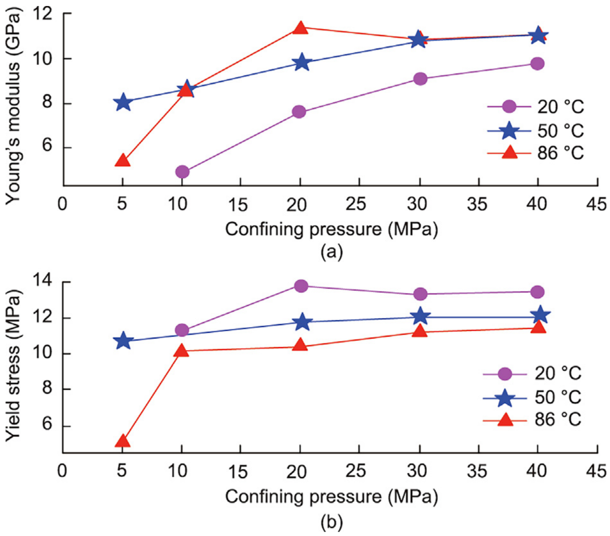

Fig. 8. Effects of confining pressure and temperature on the (a) Young's modulus and (b) yields stress of rock salt. Reproduced from Ref. [54] with permission.

temperature and confining pressure. The yield strength is insensitive to the increase of confining pressure and decreases with the increase of temperature [54]. Experimental results also show that temperature has a significant influence on the dilatancy failure of rock salt. The axial strength decreases significantly with an increase in temperature (Fig. 9) [54]. These findings confirm that temperature and stress have significant effects on the physical and mechanical parameters of rock salt, which should be given priority in describing and predicting the mechanical properties of rock salt.

Axial and uniaxial mechanical experiments with rock salt show that the micro-cracks in a sample's initial cracking (on the micron scale), expand (on the millimeter scale), and connect (on the centimeter scale), during the failure process of rock salt, resulting in the failure of the sample and the loss of its bearing capacity [55,56]. At present, there are many challenges in accurately quantifying the critical stress of failure at different scales and guiding the engineering design of salt cavern storage. This progressive multiscale phenomenon also exists in the failure of the rock mass surrounding salt cavern storage. On 3 August 2012, a salt cavern in Bayou, LA, USA, collapsed over a large area, creating a huge sinkhole in the ground. Bérest [57] analyzed that the failure of the surrounding rock mass in the lower part of the salt cavern resulted in

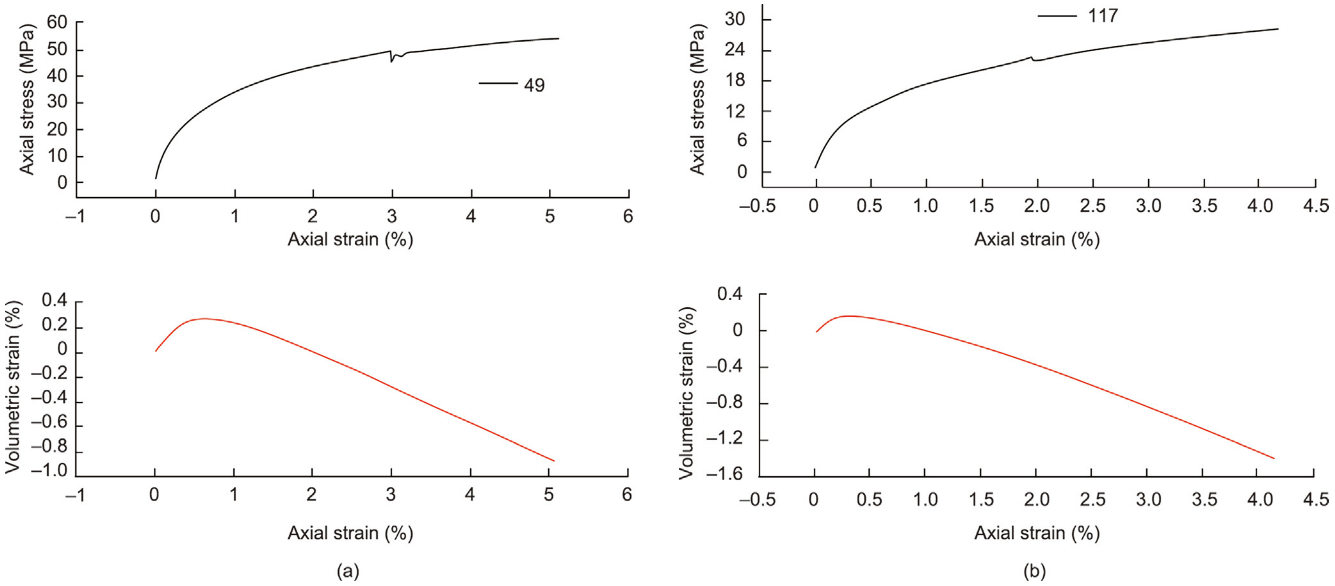

Fig. 9. Triaxial dilatancy failure envelope of salt rock under different temperatures. (a) 20 °C and (b) 86 °C. 49 and 117 are sample numbers. Reproduced from Ref [54] with permission.

the wall spalling, which then led to large-scale slip intrusion of the weak geological structure at the edge of the salt dome. This caused the overall slip and collapse of the overlying strata over 1000 m at the upper part, and finally the surface collapse.

According to the above analysis, the failure of rock salt used for energy storage is affected by chemical corrosion, temperature change, stress change, time, and scale. Available studies mainly focus on the interactions of oil, brine, and other media with the rock salt and interlayer [52,58–60], without examining the interactions of hydrogen and compressed air with the rock salt and interlayer. As a result, conclusions and understandings about the use of salt caverns for energy storage are scattered, with limitations and a certain one-sidedness. Moreover, such studies are usually carried out in laboratories, without considering the impact of scale. Therefore, there is a need for a multiscale progressive failure and characterization method for the rock masses around energy storage caverns that considers the effects of multifield and multiphase coupling, which has been proposed to be one of the basic challenges that must be studied for energy storage in deep underground spaces.

3.2. Understanding the leakage evolution of large-scale deep underground energy storage caverns

The molecular size and viscous coefficient of different energy storage media (i.e., oil, gas, compressed air, and hydrogen) differ greatly. The energy storage medium migrates into the rock mass constantly under the high pressure, which may lead to microcracking, connecting existing pores and decreasing the strength of rock masses, and may even activate geological faults. For example, leakage took place at a gas storage salt cavern in Hutchinson, KS, USA. Natural gas leaked along the completion string (Fig. 10) and migrated to shallow formations along the inclined upper Wellington shale [61]. When the gas pressure exceeded the burst pressure of the overlying formation, the high-pressure gas ruptured the overlying formation. Eventually, explosions occurred about 10 km away from the gas storage salt caverns [61]. The evolution process and impending conditions of the leakage accident remain unclear, and further research is needed on how to predict and prevent the occurrence of similar accidents in deep underground energy storage.

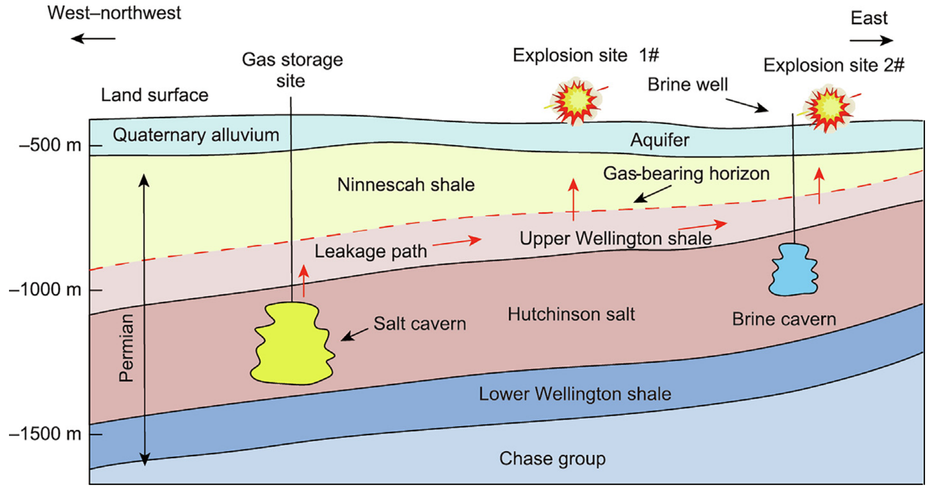

Fig. 10. Leak pathway of the Hutchinson gas storage salt cavern, KS, USA. Reproduced from Ref. [61] with permission.

Salt caverns have been widely used for natural gas and petroleum storage. Ensuring the tightness of the salt cavern is one of the most important issues [61–66]. Hou [66] found that the permeability of the damaged zone of salt rock caused by drilling increased the original permeability by 10^5 times. Chen et al. [67] established an equivalent boundary gas seepage model to study the seepage of natural gas along a weak interlayer in the rock masses surrounding a gas storage salt cavern. Xiong et al. [65] studied the seepage of natural gas along the non-salt interlayer using numerical simulation. Wang et al. [62] studied the effects of the permeability and dip angle of the interlayer and other factors on the tightness of a gas storage salt cavern. As shown by this literature review, studies on the leakage of deep underground energy storage mainly focus on salt cavern gas storage, and the only energy storage medium considered is natural gas. The influences of different energy storage media and of the surrounding rock mass, as well as multiple fields and phases, have not been considered systematically in the literature [62,65–67]. For example, methane molecules have a diameter of 0.38 nm, while hydrogen molecules have a diameter of 0.20 nm. Therefore, hydrogen molecules can leak through pores and less permeable surrounding rocks. High-pressure energy storage media migrate into the upper formation, and formation rupture and fault activation may happen when the gas pressure exceeds the bearing capacity, with disastrous consequences. However, studies on this gas leakage process and its mechanism are still rare. The injection delivery of an energy storage medium will deteriorate the rock masses surrounding the cavern and increase their permeability. Ultimately, this increases the leakage risk of the energy storage cavern. Therefore, the basic problems and research challenges for understanding the leakage evolution of salt caverns used for deep underground energy storage in China can be summarized into four aspects, as follows:

(1) Precisely predicting energy storage medium leakage and cracking of the surrounding rock mass, while considering multi-field and multiphase coupling.

(2) Determining the long-term leakage migration law of the energy storage medium.

(3) Quantitatively determining the critical disaster boundary conditions, such as pressure gradient, leakage path, leakage volume, and infiltration range of the energy storage medium.

(4) Determining the leakage disaster mechanism for deep underground energy storage groups.

3.3. Understanding the long-term performance evolution of large-scale deep underground energy storage caverns

The salt caverns used for energy storage in China generally have volumes of hundreds of thousands of cubic meters and heights of more than 100 m, and their shapes are poor (Fig. 11 [68]). Even so, the caverns must bear the comprehensive influence of the energy storage medium pressure and phase state change, which gradually deteriorate the cavern safety. These two factors make it extremely difficult to accurately predict the long-term performance and deterioration of caverns. According to the statistics on accidents in existing salt cavern oil and gas storages, long-term function failure accounts for 70% of the accidents. Therefore, ensuring the long-term performance and revealing the functional deterioration and disaster mechanism of the storage are the basic theoretical problems for energy stored deep underground.

In 2015, a sonar survey found that a massive collapse had happened of the cavern roof of a Jintan gas storage salt cavern in Jiangsu, China. The collapsed zone had a length of about 200 m, a thickness of about 2–4 m, and a volume of 3300 m^3. This collapse seriously threatened the safety of the cavern [69].

Large-scale energy storage requires the construction of cavern groups. Preventing and controlling the impact of a single cavern failure on the performance of a cavern group is another urgent problem to be solved. These challenges and problems have always been difficult and are hot issues in the fields of geotechnical engineering and underground energy storage. Staudtmeister and Rokahr [70] systematically summarized the design process and key parameters of salt cavern gas storage and considered that their proposed method could meet the long-term stability requirements of salt caverns. Langer and Heusermann [71] reported that the mechanical stability and integrity of a salt cavern were particularly important for its use as an underground hazardous waste deposal facility. They pointed out that accurate description of the surrounding rock characteristics (i.e., geological conditions, stress conditions, and the constitutive equations) is the controlling factor when evaluating salt cavern stability. Bérest [72] analyzed accidents in salt cavern gas storage and reported that the failure of a

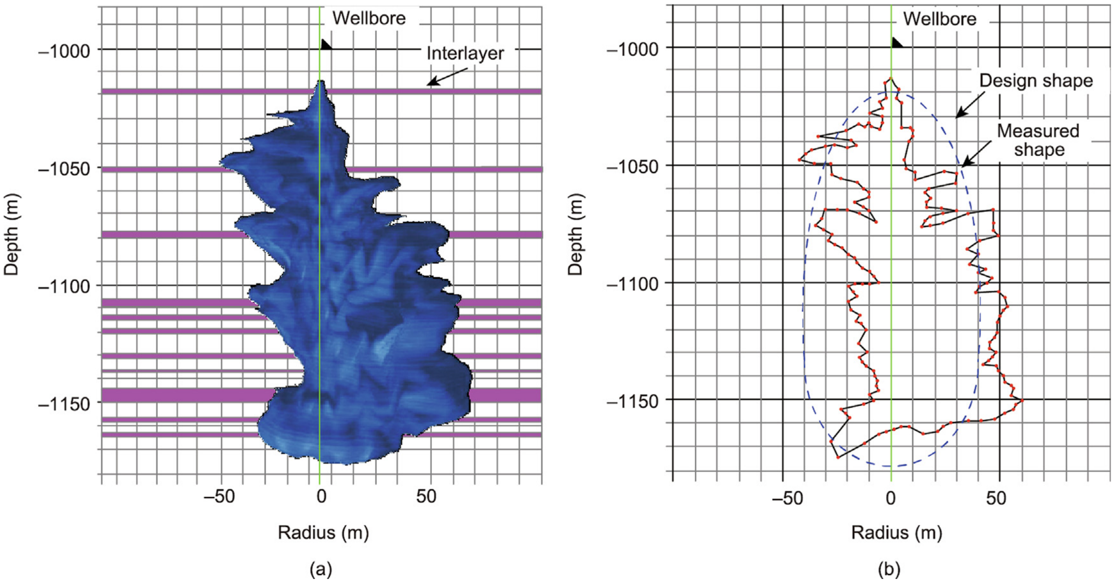

Fig. 11. Salt cavern used for natural gas storage in China with a large volume and irregular shape. (a) 3D shape and (b) 2D shape. Reproduced from Ref. [68] with permission.

salt cavern presented both brittle and plastic characteristics. They highlighted that such failure characteristics should be taken into consideration in cavern stability evaluation. Yang and his team [4,44,55,73,74] and Wang et al. [75] carried out systematic experiments on Chinese rock salt and onsite monitoring for more than 20 years. They proposed a new index system for the stability evaluation of gas storage caverns, which consists of deformation, volume shrinkage rate, plastic zone, equivalent strain, and dilatancy safety factor. The new index system has been used for the stability evaluation and operating parameter optimization of salt cavern gas storage with adverse conditions, such as those that are adjacent to old brine caverns, close to a fault, or with a small pillar width. It has been demonstrated by field production to have high accuracy and reliability.

The above studies mainly focus on salt cavern gas storage, and thus provide good references for deep underground energy storage in China. Research in the following three aspects still needs to be further strengthened:

(1) **Function evolution and potential catastrophe mechanisms of deep underground energy storage cavern farms.** To study the influence of operating parameters on the performance of a cavern group and then optimize the corresponding operating parameters, the theoretical and physical models for long-term performance evaluation of a cavern group should be studied. To predict the impact of single-cavern function failure on the safety of the whole cavern group, a catastrophe-prediction model should be established. The influence range, degree, and disaster-creating process of a single cavern failure should also be studied. The interaction mechanism of cavern groups and the theories of long-term performance evaluation and the disaster prediction of cavern groups should be focused on.

(2) **Life-cycle function evaluation of deep storage cavern groups.** A continuous and discontinuous simulation method for the functional degradation of deep storage cavern groups should be established to reveal the progressive failure process of the interaction between surrounding rock and the energy storage medium. Ground surface subsidence, energy storage medium leakage, cavern volume shrinkage, and the disaster characteristics of cavern groups should be highlighted. A whole life-cycle function evaluation system of deep storage caverns, considering the effects of surface subsidence, leakage, volume shrinkage, and stability, should be focused on.

(3) **Disaster risk assessment and control theory of deep underground energy storage caverns.** The failure modes and identification methods of deep storage caverns under the influence of single factors and multiple factors, as well as the internal correlation between different failure modes, should be studied. The sensitivity of the surrounding rock reliability of a storage cavern group to different random factors should be analyzed. The spatiotemporal response characteristics of the major disaster risk factors of deep storage caverns should be studied. The dynamic coupling relationships between disaster-inducing mechanisms and disaster-causing mechanisms, and storage cavern shape, operating parameters, and geological conditions are other basic problems that remain to be solved.

3.4. Developing intelligent construction technologies for deep underground salt caverns used for energy storage

China's rock salt is mainly bedded and has a complex geological structure. Existing salt cavern construction technology is mainly aimed at Jintan salt rock formations with preferable geological conditions [76–82]. This construction technology does not have good universality. Its disadvantage includes the formation of irregular caverns (Fig. 12) and low utilization of the salt rock formation. The construction of a cavern using water leaching method is time-consuming and directly determines the shape and volume of the cavern, which is a key process for the salt cavern energy storage [83].

Improved leaching technology is a research priority in the field of salt cavern gas storage. Brouard et al. [83] analyzed the heat exchange between the brine and rock salt surrounding a cavern during leaching and confirmed that the heat exchange was conducive to inhibiting the cavern shrinkage. Zemke et al. [84] analyzed the feasibility of injecting brine generated during cavern leaching into a deep saline aquifer. Yang and his team [77,85,86] studied the collapse control of interlayers during leaching, as well as cavern shape prediction, insoluble accumulation prediction, and a multi-step method for constructing a horizontal cavern, and used them in actual engineering. Sedaee et al. [87] developed cavern leaching simulation software based on salt dissolution and cavern shape development in a salt dome formation.

How to construct large storage caverns efficiently and quickly in China's bedded rock salt formation is a key technical problem that must be solved for the implementation of deep underground energy storage. The following three aspects of research work are needed:

(1) **Developing an efficient cavern leaching theory for bedded rock salt formation.** The theoretical model of brine flow and mass transfer during cavern leaching should be studied. The characteristics of brine flow and concentration distribution under forward and reverse circulation should be focused on. A prediction model of the fall and accumulation of insoluble impurities during cavern leaching is another critical problem. The influences of cavern leaching parameters on insoluble accumulation and its main factors are also important for improving cavern leaching efficiency. Based on this research, a theoretical system for efficient cavern leaching using the water solution method should be constructed.

(2) **Developing a physical and numerical simulation system for cavern leaching.** Efficient algorithms should be developed for prediction models of salt dissolution and insoluble accumulation and software for cavern leaching simulation should be developed based on China's bedded rock salt formation. An observation system should be built for the flow field and concentration field during cavern leaching, and a cavern shape survey instrument should be developed. Finally, a large-scale simulation experiment system for salt cavern leaching should be established to realize the accurate simulation and depiction of the whole process of actual cavern leaching for different formations.

(3) **Developing efficient and intelligent cavern leaching technology for complex formations.** For thin salt formation, high impurity contents, and local high-grade gypsum formations, the feasibility of paired wells in a small space, multi-step and back-off horizontal wells, and non-symmetric cavern construction methods should be studied. Theoretical models of these new methods should be studied first; then, the factors affecting leaching

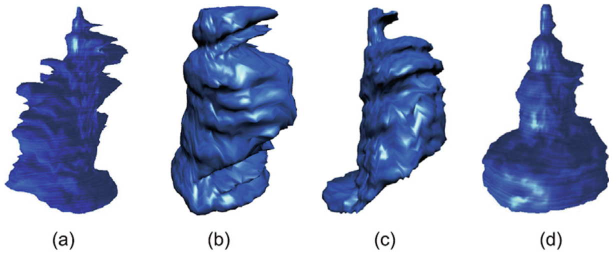

Fig. 12. 3D configurations of typical gas storage salt caverns in Jintan, China. (a) #1; (b) #2; (c) #3; (d) #4.

efficiency should be clarified. Ultimately, systematic cavern leaching technology for such complex formations should be achieved.

3.5. Ensuring the long-term function of deep underground energy storage

Due to the long service life and the flammable and explosive energy storage medium, ensuring the long-term functions (i.e., availability, sealing, stability, and safety) of energy storage caverns are a prerequisite for the implementation of deep underground energy storage. Fig. 13 presents the excessive volume losses of typical gas storage caverns [88]. The volume shrinkage can be greater than 30%, which seriously reduces the peak shaving capacity of salt cavern gas storage. In China, the long-term function assurance technology for salt cavern gas storage includes sonar surveys, surface subsidence monitoring, and micro-seismic monitoring. An et al. [89] used a sonar survey to determine that salt cavern A in Jintan, China, has a large volume shrinkage. They determined that measurement error caused by an irregular cavern shape is the main factor causing the large volume reduction of the cavern. Li et al. [90] established a theoretical model to predict the surface subsidence above a gas storage salt cavern by using the spherically symmetric displacement of a spherical cavern with shrinkage force in an elastic infinite space. The elastic analytical solution of the surface subsidence in integral form was derived accordingly. Wei et al. [91] analyzed the feasibility of using a micro-seismic method to monitor the safety of gas storage salt caverns. They concluded that a micro-seismic method can be used to monitor salt cavern stability with good accuracy. Wang et al. [92] verified the feasibility of increasing the upper operating pressure of the Jintan gas storage salt cavern through micro-seismic monitoring.

At present, research on salt caverns for the long-term function assurance of cavern groups is still in its infancy. Key questions, such as how to ensure the long-term function and safety of cavern storage, still cannot be answered. Research is suggested in the following three aspects:

(1) **Theory and technology for countering cavern volume shrinkage during energy storage.** The influence of injection–production frequency, pressure, and time on volume shrinkage should be studied in more detail. The need for a theoretical model for volume shrinkage prediction and identifying the main factors restraining the volume shrinkage of deep storage caverns under different geological conditions are also key issues. We also call for research on technology for suppressing volume shrinkage to ensure the long-term function of salt cavern storage. Technical specifications for the evaluation of the long-term availability of deep storage caverns should be determined while considering the volume shrinkage, deformation, and stress distribution around the cavern.

(2) **Long-term surface subsidence monitoring and disaster assessment for deep underground energy storage caverns.** The surface subsidence above deep underground energy storage caverns should be studied while considering the long-term coupling of the surrounding rock and the energy storage medium. The mechanisms of formation deformation and surface subsidence, as affected by operation parameters, cavern shape, and cavern layout, should be studied. Based on the leveling method and interferometric synthetic aperture radar (InSAR) technology [93], a long-term automatic monitoring network for monitoring surface subsidence should be established. A surface collapse assessment model and a safety threshold for surface subsidence should be proposed.

(3) **Long-term micro-seismic and tracer monitoring technology for deep cavern storage.** The relationship between micro-seismic signals and the failure of the rock mass surrounding deep storage should be studied. A safety evaluation and warning system for storage caverns based on micro-seismic monitoring must be established. The relationship between tracer concentration and distribution and storage leakage should be determined. Tracer concentration monitoring and an early warning system should be established, to make it possible to monitor and predict any leakage occurrence, development, and impending disaster.

4. Summary and conclusions

In summary, deep underground energy storage is one of the most effective and economical methods for large-scale energy storage, which is the main developing direction for the large-scale energy storage of China. Based on the analysis of the background,

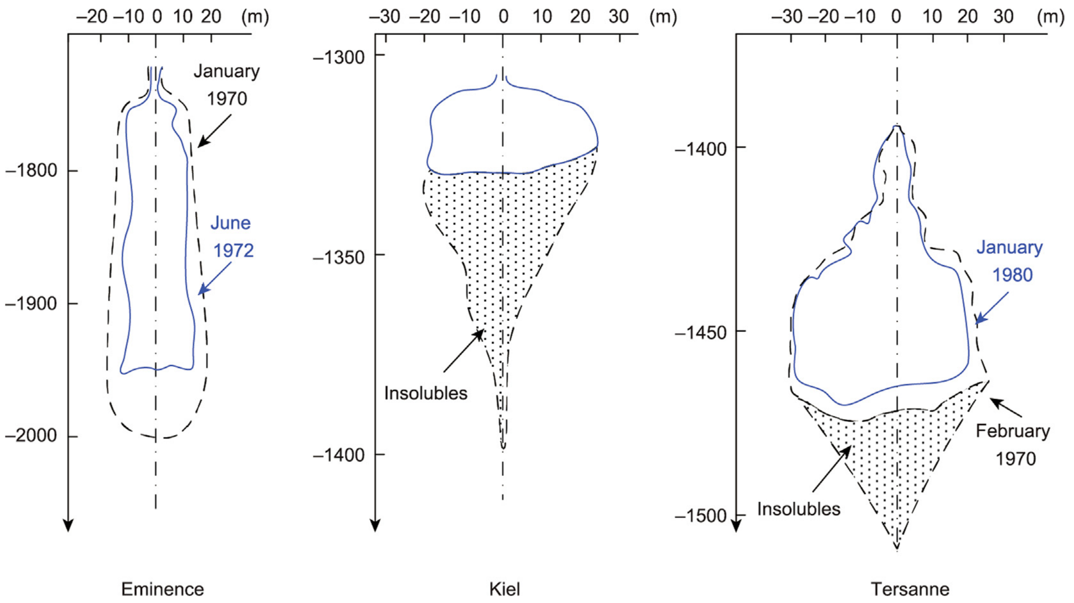

Fig. 13. Excessive volume losses of typical gas storage caverns. The dotted surfaces represent insolubles sedimented at the cavern bottom. Reproduced from Ref. [88] with permission.

types and status, and the study of the key theoretical and technical problems of deep underground energy storage in China, we make the following conclusions:

(1) The use of deep underground spaces for energy storage is an important direction for future energy reserve maintenance. It is an effective way to implement SPRs, natural gas peak shaving, a sustainable supply of renewable energy, and the large-scale and efficient utilization of hydrogen. The development of deep underground energy storage is a key issue in achieving carbon neutrality and upgrading China's energy structure.

(2) Rock salt is characterized by stable physical properties, low permeability, self-healing of damage, easy solubility in water, and a wide distribution. It is considered to be an ideal geological medium for large-scale energy storage. More than one billion barrels of oil and 3.3×10^{10} m^3 of natural gas are stored in salt caverns around the world. The utilization of salt rock for large-scale energy reserves will be the priority development direction of energy storage in China.

(3) Salt rock in China is a typical bedded rock salt with thin thickness, high impurity content, and many interlayers. It is a global challenge to construct energy reserve facilities in such formations. However, the rock salt formations in China have good locations and hold significant value for use as large-scale energy storage. It is essential to carry out the basic theoretical and key technological research on deep underground salt cavern energy storage.

(4) To use China's rock salt formations for large-scale energy storage, it is necessary to solve the basic theory and technology of several aspects of such energy storage, including: ① developing a multiscale progressive failure and characterization method for the rock mass around energy storage caverns, considering the effects of multifield and multiphase coupling; ② understanding the leakage evolution of large-scale deep underground energy storage caverns; ③ understanding the long-term performance evolution of large-scale deep underground energy storage caverns; ④ developing intelligent construction technologies for deep underground salt caverns used for energy storage; and ⑤ ensuring the long-term function of deep underground energy storage.

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Compliance with ethics guidelines

Chunhe Yang, Tongtao Wang, and Haisheng Chen declare that they have no conflict of interest or financial conflicts to disclose.

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