Risk Assessment and Monitoring Methods for Geologic Sequestration of CO_2 in the Saline Aquifer

Yiping Zhang *

School of Geosciences, Yangtze University, Hubei, China

* Corresponding Author Email: 202100789@yangtzeu.edu.cn

Abstract. Geological sequestration of CO_2 is considered to be the most effective measure to realize long-term CO_2 emission reduction, which is the key to influence the progress of carbon neutralization. In recent years, CO_2 storage in the saline aquifer has been widely utilized in many countries as it is one of the most effective ways of carbon sequestration. This paper first summarizes the geological storage mechanism of CO_2 in the saline aquifer as tectonic storage, capillary storage, adsorption storage, dissolution storage and mineral storage, and then considers the criteria for selecting the site of CO_2 in the saline aquifer in terms of technology, safety and economy. During the sequestration process, CO_2 may leak from wellbores, caprock, and fractures, and to cope with these scenarios, risk assessments are often conducted using the Delphi method, brainstorming method, risk checklist method, SWOT technique, and FEP method, among others. When targeting complex projects, the combined use of these methods can effectively improve the comprehensiveness and accuracy of risk identification, laying the foundation for subsequent risk assessment and the development of countermeasures. In order to ensure that CO_2 can be safely stored in the ground for a long time, it is necessary to implement different monitoring methods according to different purposes, which can be generally divided into three categories: CO_2 environmental monitoring, CO_2 safety monitoring and CO_2 transportation monitoring. CO_2 environmental monitoring can be divided into the atmosphere, the near-surface and the shallow stratum in terms of vertical spatial stratum distribution. The shallow stratum environmental detection technology is more mature, but due to the meteorological and topographical impact on the accuracy of atmospheric and near-surface environmental monitoring technology, generally using a combination of multi-technology for monitoring. CO_2 leakage caused by easy to cause harm, this time the use of CO_2 safety monitoring, is divided into surface deformation, stratigraphic deformation, ground stress, wellbore integrity and wellbore corrosion. We also use seismic, logging and geochemical methods to monitor CO_2 transportation.

Keywords: CCUS, saline aquifer, risk assessment, monitoring, geological storage, CO_2.

1. Introduction

Since mankind entered the era of industrial civilization in the 18th century: various types of fossil fuels have been widely used, and more and more CO_2 has been emitted into the atmosphere. The volume fraction of CO_2 in the atmosphere has risen from 0.028% in 1760 to 0.042% in 2022, and the emission of CO_2 has become a direct factor affecting global temperature and climate change and other chain reactions. The International Energy Agency (IEA) pointed out in the Energy Technology Perspectives Report 2017 that to achieve the climate goal of keeping warming at 2°C by the end of this century, Carbon Capture and Storage (CCS) technologies need to contribute 14% of CO_2 emissions reduction, and if lower warming is considered, the energy sector will need to reach net-zero emissions by 2060, and with a warming of 1.75°C by the end of the century, CCS technologies will need to contribute 32% of CO_2 emissions reduction. China also proposes to achieve carbon peaking by 2030 and carbon neutrality by 2060 [1]. To achieve carbon neutrality, it is necessary to reduce greenhouse gas emissions on one hand, and to remove greenhouse gases that have already been emitted on the other. In terms of removing greenhouse gases, in the face of such a huge amount of carbon emissions, Carbon Capture, Utilization and Storage (CCUS) is a safe, environmentally friendly, highly efficient and technically feasible means of removing CO_2. CO_2 geological storage is considered to be the most effective measure to achieve long-term reduction of CO_2 emissions, influencing the progress of carbon neutrality.

Geological storage of CO_2 usually refers to the injection of CO_2 into geological bodies with different reservoir conditions, such as deep saline aquifers, depleted oil and gas reservoirs, deep unmineable coal seams and basalts, in order to realize safe, effective and permanent carbon sequestration. Among them, the potential of saline aquifer sequestration is the largest, which is more than ten times that of depleted oil and gas reservoirs, and hundreds of times that of coal seams. CO_2 saline aquifer sequestration has been applied worldwide, such as Norway's Sleipner and Snøhvit, Algeria's In Salah, China's Shenhua, Australia's Otway and Gorgon, Canada's Quest, and the United States' Decatur [2]. However, during the process of CO_2 injection and storage, factors such as fluctuations in formation pressure can lead to rock damage in the capping layer, resulting in the risk of CO_2 leakage. It not only leads to atmospheric pollution but also affects groundwater and human safety. Therefore, it is very important to assess the risk of CO_2 leakage in geological storage.

In order to assess the risk of CO_2 leakage in a more scientific way, countries and organizations around the world have issued a series of relevant regulations and policies: the European Union formulated the Carbon Capture and Storage Directive in 2009, the United States issued Some policies, such as the Underground Injection Control Plan and the Safe Carbon Sequestration Technology Action Regulations. China issued the "CO_2 Capture, Utilization and Sequestration Technical Guidelines on Environmental Risk Assessment for Trial Use" in 2016, which involves many aspects of environmental safety assessment [3]. In addition to the assessment of the risk of leakage, continuous monitoring of CO_2 geological storage sites is also an important link to ensure the effectiveness and safety of storage. Conventional monitoring tools are mainly used to monitor changes in the geological conditions, geochemical or geophysical properties of the storage area. Geochemical means usually monitor the stratum CO_2 concentration, pH value and redox potential of water bodies, carbon isotopes and other parameters; geophysical means usually monitor the stratum temperature and pressure, resistivity, surface deformation and other parameters. However, there are many limitations in the measurement range, period and accuracy of conventional means, and they face many challenges in terms of economy and technology. Therefore, many new detection methods have been proposed, such as sensor-based online monitoring technology.

In this paper, we take the geological storage of CO_2 in the saline aquifer as the target, introduce the storage mechanism and the site selection criteria, discuss the potential risks of geological storage and the risk identification and assessment methods, and the monitoring approaches of CO_2 storage from the aspects of environment, safety and transportation.

2. Overview of geological storage of CO2 in saline aquifer formations

2.1. Sequestration mechanism

The ways of CO_2 geological storage and its mechanism include:

1) Tectonic storage: the use of stratigraphic tectonic closure for storage, this is the main way of geological storage in the early stage, which is the basic condition of CO_2 geological storage; 2) Capillary storage: affected by the differences in the structure of the pore throat of the reservoir rock and the pore capillary pressure, the use of capillary force to prevent the CO_2 from continuing to rise. Part of the CO_2 gas remain in the reservoir pore space; 3) adsorption storage: CO_2 on the surface of the pore space of the reservoir rock produce a stronger physical adsorption, much stronger than the adsorption of methane, so as to replace the methane, and to achieve the role of strengthening the exploitation of gas resources in the reservoir at the same time as the sealing of CO_2, this sealing mechanism is mainly in the oil and gas reservoirs and the deep coal beds; 4) solubilization Sequestration: Utilizing the dissolution of underground water in the reservoir for sequestration, CO_2 mainly exists in water in the form of dissolved state; 5) Mineral sequestration: Utilizing the reaction between CO_2 and rock to form stable carbonate minerals for sequestration, mainly used in the geological sequestration of CO_2 in basaltic rock, which is the most stable sequestration method and takes the longest time (Table 1).

Table 1. CO_2 geological storage mechanism.

storage mechanism	feature description	
	sequestration characteristics	Limitation conditions and favorable conditions of storage characteristics
Structural storage	Driven by buoyancy, sealed in anticlines, folds, faults and pinchouts.	Without hydrodynamic drive, limited by the fluid compression coefficient. With hydrodynamic system, displaces the formation fluid.
Residual storage	CO2 filling in the pores of the rock skeleton	Can take up 15-20% of the storage space
Adsorption storage	CO2 adsorption on the pore surface of reservoir rocks	Enhanced extraction of gas reservoir resources while sequestering CO2
solubility trapping	CO2 dissolved in strata water	limited by the contact relationship between CO2 and water
mineral carbonation	CO2 reacts with surrounding rocks to form new minerals.	Slow reaction rate and precipitation of minerals reduces injection capacity

2.2. Site selection criteria

The establishment of sound selection criteria for storage sites is a prerequisite for selecting suitable storage sites and ensuring safe storage. In this paper, the site selection criteria are divided into three major dimensions: technical, safety and economic (Table 1).

The technical indicators mainly include the macro characteristics of the reservoir, geothermal characteristics, physical properties and injection capacity. The injection capacity is controlled by formation lithology, reservoir connectivity, high permeability and relatively low pore pressure. Safety factors need to take into account the confinement of the cap rock to the reservoir CO_2 sequestration and the stability of the injection project to the formation itself, and the high seismicity area should be excluded. The cap rock not only needs to be thick, continuous and effective, and preferably there should be several sets of continuous and stable buffer layers, but also the lithology needs to remain chemically inert to CO_2 for a long period of time. The injection project should not trigger earthquakes, especially the stability of the formation around the injection wells and the effectiveness of the drilling tubing column, and there should be a comprehensive long-term monitoring and leakage prevention and treatment program for the stability of the faults and the activity of the cracks. Economic factors include the distance to the source and sink, the storage method and the infrastructure. For large amounts of CO_2 injection, storage should be as close as possible, or specialized CO_2 gathering pipelines should be considered [2].

3. Risk identification and assessment of geological storage of CO2 in saline aquifer formations

3.1. Potential risks

The safety risks of carbon sequestration mainly lie in the leakage of CO_2. One of the prerequisites for the siting of CO_2 geological sequestration is the existence of a good confinement mechanism. There is still a risk of leakage from CO_2 geological sequestration due to operational errors or mechanical failures in the injection wells or through leakage pathways such as wellbores, capping, faults and fissures.

CO_2 geological storage leakage risk is divided into global risk and local environmental risk. Global risk is the leakage of sequestered CO_2 into the atmosphere, which may trigger significant climate change. Local environmental risk is the impact of leakage on the local environment and even human health and safety. CO_2 is a gas widely found in nature, and its normal concentration is around 0.04%, although it is non-toxic, but if it is exposed to a higher concentration of CO_2, it also has impacts on human health and environment. Therefore, the geological storage of CO_2 must be addressed to ensure that it can be used in a sustainable manner. It is necessary to evaluate the risk of leakage of CO_2 geological storage, identify the environmental risks, and provide technical support for avoiding environmental risks and taking appropriate risk management measures.

Benson proposed a schematic diagram of the evolution of the risk of CO_2 geological storage. It shows that the leakage risk gradually increases with the beginning of CO_2 injection, and the leakage risk reaches the maximum with the end of injection. After the site is closed, the risk of leakage decreases with the passage of time [4].

3.2. Risk Identification Factors and Methods

3.2.1. Factors

The safety and reliability of geological storage of CO_2 is directly related to the successful implementation of the project and its long-term environmental benefits. Therefore, it is crucial to accurately identify the potential risks in the process of CO_2 geological storage.

During the long-term injection and storage of CO_2, there are three possible CO_2 leakage pathways: the wellbore, the cap rock and faults/fractures (Figure 1). Understanding the mechanisms of CO_2, monitor the abnormal CO_2 transportation, and adopt appropriate strategies to reduce the probability of CO_2 leakage. Analyzing and summarizing different leakage pathways and comparing their leakage characteristics are the key to ensure the safety of CO_2 storage, and also provide a technical decision basis for the selection of storage process [5].

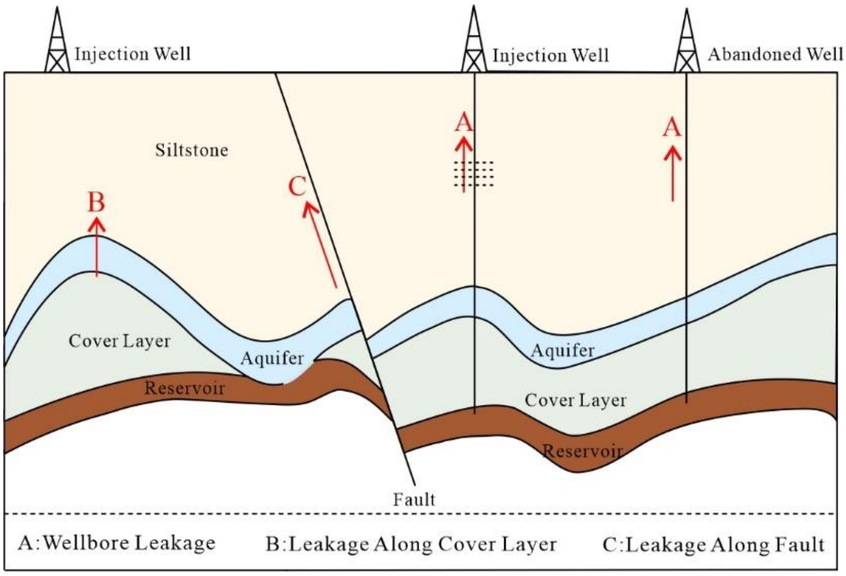

Fig 1. CO_2 geological storage's major leakage pathways.

1) CO_2 leakage through wellbore

CO_2 is injected into the formation through the only channel of injection wells, and usually due to chemical or mechanical effects, CO_2 leakage occurs along the drilling cement ring, wellbore bridge plugs, or perimeter rock fracture zones [6]. Wellbore leakage is usually influenced by a variety of factors, among which the effects of construction work, tensile damage caused by alternating stress during CO_2 injection and chemical corrosion are more obvious. Mechanical reactions are mainly due to CO_2 injection, temperature reduction or pressure increase, resulting in cracks in the cement ring or casing contraction, thus reducing the sealing of the leakage triggered. After a long period of CO_2 injection, chemical reactions are mainly corrosion, leading to a risk of perforation of the casing as well as cracks in the cement ring.

2) CO_2 leakage through cap rock

The cap rock is not only an effective barrier to prevent upward migration of CO_2, but also a leakage channel. The cap rock has high mud content, large sediment thickness, low permeability and high capillary pressure. When CO_2 is injected into the stratum, due to its small density, it gathers at the top of the cap rock under the action of buoyancy. With the long time contact between CO_2 and cap rock, chemical reaction occurs, increasing permeability and porosity, destroying the integrity of the cap rock, and greatly increasing the risk of CO_2 leakage [3]. When the permeability of the cap rock is relatively high, it is easy to develop small cracks or fractures, indicating that there may be a large number of gaps and channels in the cap rock, and CO_2 always leak through these cracks and break through the cap rock. When the permeability of the cap rock is low, the leakage rate is very low [7]. It has been shown that CO_2 leakage leads to a decrease in the pH of the groundwater in the cap rock, dissolution of minerals, and an increase in the permeability of the cap rock. The dissolution and precipitation of minerals lead to small changes in their structure, and CO_2 leads to a decrease in confinement efficiency, which is transmitted to the cap rock more quickly, causing a significant increase in permeability.

3) CO_2 leakage through faults/fractures

With the continuous injection of CO_2, the pressure of underground reservoir keeps gradually increase. The excessive pressure may exceed the breakthrough pressure of the cap rock, affecting the pressure balance of the stratum, resulting in the occurrence of cracks in the cap rock, the movement of the fault surface, and even the loosening of the originally closed faults, triggering the leakage of CO_2 through multiple channels [3]. Some studies show that the main factors affecting CO_2 leakage along faults and cracks are crack opening, effective permeability, injection depth, and injection rate and reservoir inhomogeneity. When CO_2 is injected into the brine layer, the faults in the cap rock may be activated because the pressure in the brine layer increases after CO_2 injection, and the fluid pressure along the faults also increases. When the faults are activated, the faults become leakage channels for fluids, and in order to prevent the formation of new leakage paths, the aquifer pressure must be kept below the critical pressure.

3.2.2. Methodologies

Risk identification methods are a very important part of the management and decision-making process and help in identifying and assessing various risk factors that may affect the achievement of the objectives of a project or organization. Among them, Delphi method, brainstorming method, risk list method, SWOT, and FEP method are commonly used qualitative risk identification methods. For example, the risk list method systematically identifies risks by listing possible risk events and their characteristics. SWOT technique reveals potential risks by analyzing the organization's internal strengths and weaknesses, as well as external opportunities and threats. The FEP method can be semi-quantitative by means of expert opinion, collective discussion and expert interviews for risk matrix assessment. Risk graphical analysis techniques are also a commonly used risk management tool aimed at presenting risk information graphically so that decision makers can see more clearly the correlation between risks and the degree of impact, including bow-tie method, Failure Mode and Effects Analysis (FMEA), Fault Tree Analysis, and Bayesian Network Analysis. Table 1 summarizes the risk identification methods from the proposed time, considerations, implementation process, advantages, shortcomings, applicable conditions, and applications. When targeting complex projects, the comprehensive application of these methods can effectively improve the comprehensiveness and accuracy of risk identification, laying the foundation for subsequent risk assessment and countermeasure development [8].

3.3. Risk assessment methodologies

Based on the factors of risk identification, the CO_2 leakage risk determination indicators (in ascending order of risk contribution) include:

Indicators of basic wellbore information include the following indicators: a) Number of wellbores: if other wellbores already exist near the injection wells at the time of project location selection, the possibility of CO_2 leakage through the existing wellbores could increase. When selecting the location of injection wells, dense areas of wellbores with leakage risk should be avoided, and areas with low drilling density should be prioritized and recommended for carbon dioxide storage; b) well slope: when the well slope increases, the possibility of problems with cementing quality increases, and the risk of leakage is also higher; c) type of drilling: generally, in-use oil and gas production wells, gas injection wells, water injection wells, monitoring wells and so on, have less influence on the occurrence of leakage, but if the wellbores have been abandoned, then the impact on leakage could be less than that of the wellbores. However, if the wellbore is abandoned, the risk of leakage increases due to lack of maintenance; d) Well completion time: the completion time of the wellbore is an important factor affecting the risk of leakage; e) Cementing conditions: cementing conditions such as quality of cementing, sealing length, and length of cement plugs have a significant impact on the risk of leakage; and f) History of accidents: if an accident such as overflow or well gushing has occurred on a wellbore before, then the well could have a high risk of leakage.

Indicators of fault conditions include: a) Fault activity rate: Fault activity rate is used to measure the activity of faults. The higher the value, the higher the fault activity and the higher the risk of leakage; b) Fault Mud Ratio: Fault mud ratio is used to measure the lateral closure of the fault. The higher the value, the higher the possibility of mud shale and mud coating in the fault, and the higher the possibility of lateral closure; c) Fault location: according to the provisions of GB17741, the near-field range of the seismic safety evaluation of Class I site should be extended to a radius of 25km. If there is a fault with strong activity and poor closure within 25km radius of the injection well, it is considered that the risk of leakage of CO_2 geological storage project site is high.

The basic information indicators of the storage geological body include: a) reservoir depth: the injection of CO_2 needs to reach the supercritical state in order to increase the storage capacity of CO_2; b) reservoir thickness: a thicker reservoir is more suitable for the storage of CO_2 and reduces the risk of leakage; c) reservoir pressure coefficient: lower initial reservoir pressure coefficient is favorable for the injection of CO_2 and reduces the possibility of a significant build-up of pressure, thus reducing the risk of leakage; d) reservoir porosity and average lateral permeability: higher reservoir porosity and permeability are favorable for CO_2 injection and can reduce the possibility of significant pressure accumulation, thus reducing the risk of leakage. The average lateral permeability has the most significant effect on the amount of CO_2 and injection capacity; e) reservoir lithology: sandstones and carbonates react moderately with CO_2, while basalt reacts more rapidly with CO_2, with the possibility of excessive dissolution of minerals, which affects the stability of the stratum; f) reservoir saline aquifer mineralization: the lower the mineralization, the greater the amount of CO_2 that can be chemically sequestered; g) Thickness of cap rock: for underground saltwater layer storage, the greater the thickness of the cap rock, the lower the possibility of leakage of injected CO_2 breaking through the cap rock. The thickness indicators to be considered are the thickness of the cover layer immediately adjacent to the reservoir and the cumulative thickness of the cover layer to the surface; h) Coverage of the cover layer: if the cover layer can cover the range of the CO_2 plume in the reservoir and its distribution is basically continuous, the risk of CO_2 leakage could be significantly reduced; i) Integrity of the cover layer: if there is a complete combination of reservoir and cover layer, and the sealing of the cover layer is good and there is no fissure or the distribution of the fissure is relatively discrete, the risk of CO_2 leakage risk is significantly reduced; j) cap permeability: lower cap permeability is conducive to long-term storage of CO_2 in the reservoir, which significantly reduces the risk of CO_2 leakage through the cap; k) temperature: lower reservoir temperature increases the density of CO_2, and at the same time reduces the buoyancy of CO_2, which reduces the risk of CO_2 leakage.

For the listed indicators for determining the risk of CO_2 leakage, the scoring method is usually adopted to give the corresponding score for each indicator, which reflects the possibility and severity of the risk of leakage in the CO_2 geological utilization and storage project. For example, 0.2, 0.4, 0.6, 0.8 and 1 points correspond to high risk, high risk, medium risk, low risk and basically no risk, respectively. The scores for each indicator are multiplied together and the total CO_2 leakage risk of the project is judged based on the final multiplication result.

4. Means of monitoring geological storage of CO_2 in the saline aquifer

The monitoring and evaluation of the effectiveness of CO_2 geological storage is to ensure that CO_2 can be safely stored in the ground for a long period of time.

There are many kinds of monitoring techniques, such as conventional monitoring, geophysical monitoring, geochemical monitoring, tracer monitoring, microseismical monitoring, remote sensing monitoring and infrared detection. These techniques can be categorized based on their specific purposes: CO_2 environmental monitoring, CO_2 safety monitoring, and CO_2 transportation monitoring. According to different monitoring purposes, they can be divided into CO_2 environmental monitoring, CO_2 safety monitoring and CO_2 transportation monitoring.

CO_2 leakage monitoring is a long-term endeavor, and the monitoring required is expected to continue for decades once injection operations cease. Overall, there is still much room for progress in the development of these monitoring systems, which still need to be continuously optimized and improved. While significant advancements have been made in monitoring technologies, there remains considerable potential for further development and optimization of these systems to ensure their effectiveness and reliability over time.

At present, there are many CO_2 monitoring methods, expensive instruments and equipment, and no perfect standards have been formed, so there is an urgent need to establish a comprehensive CO_2 leakage monitoring system integrating multi-layer environmental monitoring and multi-angle safety monitoring, which usually involves a large amount of complex data processing, and the evaluation indexes of the monitoring accuracy are yet to be perfected, so the research focus will be on a combination of synergistic techniques based on the traditional single logging technology, which has obvious advantages. On the basis of traditional single logging technology, multiple synergistic technologies with obvious advantages will become the focus of research. As carbon reduction technology becomes more mature, a perfect and accurate CO_2 monitoring system is the key to the success of geological storage projects [5] (Figure 2).

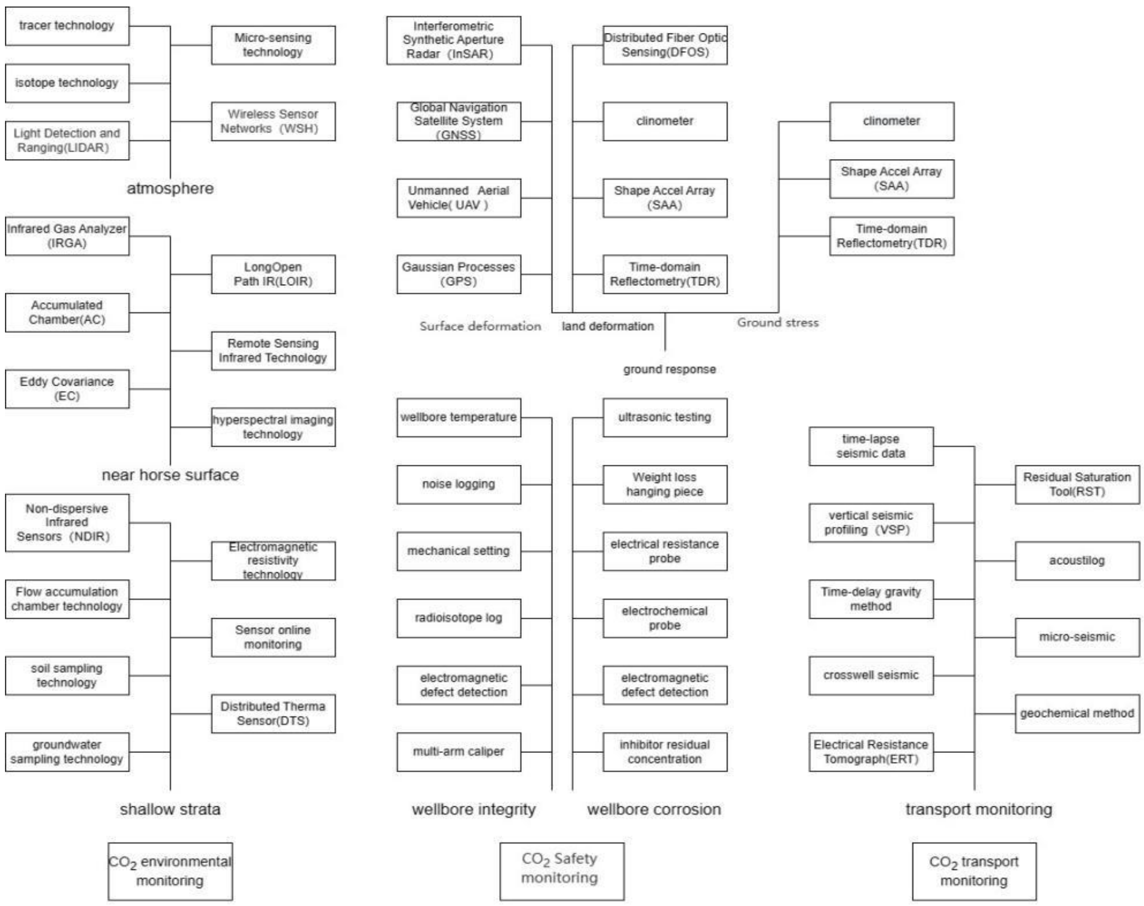

Fig 2. CO_2 environment, safety, and transport monitoring technology system.

4.1. CO_2 environmental monitoring

According to the vertical spatial stratigraphic distribution, CO_2 environmental monitoring can be categorized as atmospheric, near-surface and shallow stratigraphic.

Common atmospheric monitoring techniques include tracer technology, isotope technology, Micro-sensing technology, Light Detection and Ranging (LiDAR) [9], Wireless Sensor Networks (WSH). Atmospheric environmental monitoring mainly involves the continuous sampling and measurement of atmospheric CO_2 in the storage area, which helps to find CO_2 concentrations different from the ambient background values and to determine the location of CO_2 leakage. Generally, several CO_2 monitoring points are set up in the vicinity of the storage site or even within a few kilometers around the site to carry out continuous automatic monitoring and to collect the relevant data. The CO_2 concentration in the atmosphere is high, the source is complex and fluctuates with time and space, and the trace CO_2 leaked during the storage process is likely to be submerged in the background concentration fluctuations, which makes it difficult to be recognized and monitored.

Common near-surface environmental monitoring techniques include Infrared Gas Analyzer (IRGA), Accumulated Chamber (AC), Eddy Covariance (EC) [10], Long Open Path IR (LOIR) [9], remote sensing infrared technology and hyperspectral imaging technology. Near-surface environmental monitoring mainly focuses on CO_2 concentration, CO_2 flux, plant growth and meteorological conditions. Since CO_2 concentration is larger than air and tends to accumulate in poorly ventilated or low-lying areas, the monitoring points should be set up at environmentally sensitive points such as sealed wellheads, downwind of the dominant wind direction, and low-lying areas. Near-surface monitoring can be heavily influenced by topography and weather conditions, but a variety of common near-surface environmental monitoring techniques have their own limitations, for example, although IRGA has high accuracy and fast response, but can’t accurately calculate the amount of leakage and is not easy to measure the area of the region; AC is mainly aimed at the measurement of the concentration of CO_2 in a small area, the monitoring range is limited; EC can monitor a large area but is susceptible to the external environment interference; LOIR Although the detection range is flexible and covers a wide area [5], there are some limitations. Because of this, making it difficult to detect trace CO_2 leakage with a single technique. Therefore, a combination of monitoring technologies, informed by successful domestic and international projects, should be employed to optimize near-surface monitoring in specific geological environments.

Shallow stratigraphic monitoring techniques include Non-dispersive Infrared Sensors (NDIR), flow accumulation chamber technology, soil sampling, electromagnetic resistivity, groundwater sampling, Sensor online monitoring, and Distributed Therma Sensor (DTS) [11]. The main purpose of shallow stratigraphic environmental monitoring is to identify the leakage of CO_2 in the shallow stratigraphic environment. Shallow stratigraphic environmental monitoring is mainly used to determine CO_2 leakage by monitoring changes in various parameters in soil and groundwater. At present, shallow stratum environmental monitoring technology has been relatively mature, soil monitoring focuses on considering soil environmental indicators and monitoring stratum, combined with space and time system, forming a three-dimensional, multi-parameter, long-term soil monitoring system applicable to different terrain and geomorphology. For groundwater monitoring, the research and development and optimization of U-tube stratified sampling device has become the mainstream technology in China. At the same time, in order to meet the demand for higher precision, the development of multi-layer groundwater in-situ monitoring technology has become an important research direction for groundwater monitoring in the future.

4.2. CO_2 safety monitoring

With the continuation of oil and gas field development time, well casing deformation, corrosion, fracture and other phenomena occur from time to time, the early small leakage may be gradually aggravated, bringing serious potential hazards to the wellbore and production safety. CO_2 safety monitoring is mainly based on the direct hazards caused by CO_2 leakage, which can be categorized into surface deformation, stratigraphic deformation, geostress, wellbore integrity and corrosion of the wellbore.

The surface deformation is due to the fact that the pressure of the target formation increases with the CO_2 injection. When the CO_2 plume diffuses and accumulates in the upper part of the formation, the pressure gradually be transmitted to the upper part of the formation. The surface eventually shows slow uplift and elevation deformation in the vicinity of the injection wells. Nowadays, surface deformation measurements are often carried out by interferometric synthetic aperture radar (InSAR) [12] technology. In addition, surface deformation can also be observed before and after CO_2 injection by means of Global Navigation Satellite System (GNSS), Unmanned Aerial Vehicle (UAV) remote sensing, Global Positioning System (GPS) [11] and other technologies, and surface deformation can be determined by comparing temporal and spatial baselines, seasons and other data. However, the surface deformation monitoring technology is easily affected by factors such as climate conditions, vegetation conditions and topographic relief, and it cannot sense internal stratigraphic activities, which leads to lagging monitoring data and makes it difficult to realize early warning.

Stratigraphic deformation is mainly through the analysis of deep deformation data, combined with triggering factors and deformation patterns to determine whether the CO_2 leakage. It can be complemented with the surface deformation, to achieve three-dimensional monitoring effect. The monitoring methods of stratigraphic deformation mainly include distributed fiber optic sensing (DFOS) [13], inclinometer, Shape Accel Array (SAA), Time-domain Reflectometry (TDR) [12]. Among them, DFOS has been widely used in the field. Among them, DFOS has become the preferred technology for stratigraphic deformation monitoring, and when CO_2 leakage occurs, the displacement changes lags behind the stress change, so the monitoring of stress can be more early warning, and the monitoring effect is remarkable. Ground stress monitoring methods are mainly capacitive pressure sensors, fiber optic pressure sensors, strain pressure sensors. Deformation monitoring is more often used in practical engineering applications. But the monitoring of geostress is relatively less, which is mainly because the deformation monitoring data is more intuitive and easier to realize compared with the geostress.

Wellbore integrity runs through the whole life cycle of CO_2 geological storage program, and wellbore integrity monitoring has important research significance and engineering value for the safe production of oil and gas wells. Currently, the main monitoring methods include noise logging, mechanical setting, isotope tracing, wellbore temperature profiling, as well as electromagnetic flaw detection and multi-arm well path technology as auxiliary measurements of tubing leakage. Compared with single or traditional techniques, the combination of logging techniques has more obvious advantages, and can evaluate wellbore integrity from multiple angles and in all directions.

4.3. CO_2 transport monitoring

It is of great significance to grasp the transportation of CO_2 after storage to ensure the long-term stability and safety of CO_2 flow plume. The horizontal transportation of CO_2 is less dangerous, but the focus is on the vertical upward transportation. The greater the distance of CO_2 upward transportation, the lower the safety of CO_2 storage, the more likely to cause CO_2 leakage. From the perspective of monitoring methods, the main methods for monitoring CO_2 transportation are seismic method, well logging method and geochemical method.

1) Seismic monitoring technologies

Seismic monitoring technology is used to determine the information of CO_2 distribution range, pressure, sequestration, oil drive efficiency and leakage status, by comparing the time and amplitude difference before and after CO_2 injection.

Time-shifted seismic is one of the most important monitoring methods in transport monitoring, which is usually categorized into three-dimensional seismic and four-dimensional seismic. 3D seismic utilizes multiple seismic sources and receivers to obtain stratigraphic images, which can obtain reservoir rock information and is conducive to obtaining time-lapse images of CO_2 plume transport. Four-dimensional seismic is to repeat 3D seismic monitoring at the same observation point and different observation times to monitor the fluid changes in the reservoir, and the obtained data sets can be processed in different moments of 3D images to monitor the fluid leading edge and the effect of fluid dynamic characteristics.

The distribution of CO_2 in the formation can be better imaged by using time-lapse seismic method. Vertical Seismic Profiling (VSP) [14] utilizes the geological body of the formation to detect and receive the transmitted periodic seismic wave response signals, and can accurately obtain information on CO_2 concentration and transport in the area near a single well, and the monitoring area can be expanded by implementing VSP with multi-variable well source distance methods. This technique plays an important role in both on-site characterization and time-delayed monitoring, and has become the first choice for CO_2 transport monitoring, and has made remarkable progress in engineering projects in many countries.

The time-delayed gravity method, which utilizes measurements of spatial variations in the gravitational field resulting from changes in subsurface mass density, can be used to monitor and characterize a number of dynamic processes. The technique is sensitive to density changes due to fluid substitution and can monitor the full range of CO_2 saturation. As demonstrated by the Norwegian Sleipner project [5], which used submarine gravity to monitor a CO_2 plume for nearly 20 years and produced a time-delayed gravity response that was much higher than the sensitivity and measurement repeatability of current instruments.

Inter-well seismic places the seismic source and receiver separately in adjacent wells for monitoring, which can obtain information on reservoir structure, fluid distribution, gas injection effect and trace CO_2 leakage between wells, and realize the monitoring of CO_2 transport and distribution between wells.

The microseismic method can reflect the change rule of pressure and gas transportation in the storage area and aquifer by monitoring the change of formation pressure or small vibration events during CO_2 injection, and the microseismic events also have obvious correlation with the CO_2 injection rate. Acoustic signals generated during hydraulic fracturing or high-flow injection can be used to determine the location of microseismic events, and the injection of CO_2 has caused the reactivation of many small faults in the underlying basement of the reservoir. The distribution of microseismic events is well correlated with the distribution of CO_2 transport plume, but the overall seismic events are not strong and did not cause obvious geomechanical deformation in the reservoir.

2) Well-logging technology

Well logging technology can be based on seismic detection, the use of resistivity on the medium porosity, permeability and other sensitive features of the monitoring of the target layer to assist in monitoring.

Electrical Resistance Tomograph (ERT) relies on a powerful data collection system to realize subsurface transport imaging by utilizing the characteristics of resistivity change of reservoir fluid after CO_2 injection [15]. ERT can acquire valuable information independently of all seismic methods and has a high repetition rate and low cost.

Residual Saturation Tool (RST) can provide CO_2 saturation profiles at well locations over time, and ERT in combination with it can potentially map CO_2 saturation in the inter-well cross section. CO_2 saturation has a small effect on resistivity, resulting in small variations in the induced log response in partially saturated reservoirs. Linear RST tools can detect changes in water saturation due to CO_2 injection using pulsed neutron trapping.

Acoustic logging is a new technique for vibration detection using fiber optic sensing, which is particularly suitable for permanent burial and long-term monitoring. In the formation, because of the obvious difference in sonic velocity between water and CO_2, changes in the CO_2 flow plume through the wellbore can be assessed by sonic logging. This technique could obtain changes in the time interval of CO_2 presence and changes in the electrical conductivity and radioactivity of the formation after the geological sequestration of CO_2.

3) Geochemical technology

Geochemical technology is simple, easy to operate, time-sensitive, and has an absolute advantage in the transportation of CO_2 after injection. Data are collected prior to injection, a baseline is established, and tracers are used to repeatedly test and monitor CO_2 transport or to evaluate the geochemical changes in the reaction between the brine saturated with CO_2 and the reservoir. At the same time, it can provide calibration data for numerical simulation, which is easy to be widely applied, and combined with seismic method.

5. Conclusion

The mechanism of geological storage of CO_2 in the saline aquifer includes tectonic storage, capillary storage, adsorption storage, dissolution storage and mineral storage. When selecting a site for CO_2 in the saline aquifer, consideration should be given to the three major dimensions of technology, safety and economy. Among them, the technical indicators mainly include the reservoir's macroscopic characteristics, geothermal characteristics, physical properties and injection capacity. Safety factors need to consider the tightness of the cap rock to the reservoir CO_2 storage and the stability of the injection project to the formation itself. Economic factors include the distance between the source and sink, the storage method and the infrastructure.

During the long-term injection and geological storage of CO_2 in the saline aquifer, there are three possible CO_2 leakage pathways: wellbore, cap rock, fault or fracture. Analyzing and summarizing different leakage pathways is the key to ensure the safety of CO_2 storage. In risk identification, risk identification methods, such as Delphi method, brainstorming method, risk list method, SWOT technique, and FEP method, could be selected from the aspects of time of proposal, considerations, implementation process, advantages, shortcomings, applicable conditions, and applications. When targeting complex projects, the comprehensive use of these methods can effectively improve the comprehensiveness and accuracy of risk identification, laying a foundation for subsequent risk assessment and the development of countermeasures.

Monitoring and evaluation of the effectiveness of CO_2 geological storage is to ensure that CO_2 can be safely stored in the ground for a long period of time. According to different monitoring purposes, it can be divided into CO_2 environment monitoring, CO_2 safety monitoring and CO_2 transportation monitoring. CO_2 environmental monitoring can further be divided into atmospheric, near-surface, and shallow stratum monitoring, based on vertical stratigraphic distribution. Atmospheric and near-surface environmental detection techniques are easily affected by meteorology and topography, and the accuracy of detection decreases, requiring the use of multiple forms of technology combinations to realize monitoring. In comparison, the shallow formation environmental detection technology is more mature. CO_2 safety monitoring is mainly based on the direct harm caused by CO_2 leakage, which can be divided into surface deformation, stratigraphic deformation, geostress, wellbore integrity and wellbore corrosion. CO_2 transport monitoring methods mainly include seismic, well logging and geochemical methods. Usually, a combination of monitoring techniques has a better performance. Usually, a combination of monitoring techniques has more obvious advantages.

References

[1] Zhang Guangqi, Xu Yubing, Liu Zengqi, Xu Zhen, Wang Yiwei, Sun Qiang, Research Progress on CO_2 Geological Storage Technology, Modern Chemical Research, 2024, (17): 41-43.

[2] MA Xinrui, LIANG Jie, LI Qing, YUAN Yong, CHEN Jianwen, LUO Di, ZHAO Hualin, SONG Peng, Progress and prospects of CO2 geological storage in saline aquifer, Marine Geology Frontiers, 2024, 40(10): 1-18.

[3] BAI Yunyun, SHI Yangyang, LU Meijuan, LIANG Ying, Research Progress of CO_2 Geological Storage Leakage Path and Monitoring Method under Dual Carbon Targets, JOURNAL OF YULIN UNIVERSITY, 2021, 31 (06): 43-46.

[4] Li Ke, Han Xiaojun, Zhang Xiaobin, Liang Bo, Hu Feng, Wang Qingchuan, Sun Jian, and Wang Songting, Evaluating the key controls on CO_2 geologic storage site, Natural Gas Exploration And Development, 2024, 47 (05): 95-102.

[5] Wang Zhanpeng, Liu Qi, Ye Hang, Zhang Min, Liu Shuangxing, Weng Yibin, research progress on CO_2 geological storage leakage and monitoring, Environmental Engineering, 2023, 41 (10): 69-81.

[6] VIALLE S, DRUHAN J L, MAHER K. Multi-phaseflow simulation of CO, leakage through a fractured caprock in responseto mitigation strategies, International Journal of GreenhouseGas Control, 2016, 44:11-25.

[7] CIHAN A, BIRKHOLZER J T, ZHOU Q. Pressure buildup and brine migration during CO_2 storage in multilayered aquifers. Groundwater, 2013, 51(2):252-267.

[8] Jing Meng, Li Qi, Liu Guizhen, Xu Xiaoyi1, and CO2 Geological Storage Risk Identification: Methods and Application, Chinese Journal of Environmental Engineering, 2024, (10): 2719-2728.

[9] Wang Xaoqiao, Ma Denglong, Xia Fengshe, Zhang Xiaoming, Wang Yu,Mao Weigao, Research Progress on Leakage Monitoring Technology for CO, Storage, Safety and Environmental Engineering, 2020, 27 (02): 23-34.

[10] Yang Hui, Fan Huaiwei, Wang Wenfeng, Zhang Yunhui, Ju Wei, Qin Yong, Air-Ground iInteg Rated Monitoring Method of Leakage Risk During Geological Carbon Sequestration, Journal of Engineering Geology, 2023, 31 (04): 1461-1473.

[11] Xu Liang, Cheng Gang, Zhu Honghu, Research Review of Landslide Monitoring Methods Based on Integration of Space-Air-Ground-Interior, Laser & Optoelectronics Progress, 2021, 58 (09): 98-111.

[12] DENG Lizheng, YUAN Hongyong, ZHANG Mingzhi, CHEN Jianguo, Research progress on landslide deformation monitoringand early warning technology , Tsinghua Univ(Sci & Technol) 2023, 63 (06): 849-864.

[13] Lu Yi, Song Zezhuo, Liu Jin, Bu Fan, Qi Chang qing, Land subsidence monitoring and deformation analysis ofTongzhou Bay area based on DFOS, Journal of Hohai University(Natural Sclence), 2023, 51 (02): 81-88.

[14] Zhang Yuehua, Liu Yan, Lv Qingtian, Chen Zhaoxi, Yan Jiayong, Research progress and application prospect of geophysical monitoring technology in the carbon dioxide geological storage, Geology in China, https://link.cnki.net/urlid/11.1167.P.20240527.1112.002

[15] ZHANG Qi, CUYongjun, BU Xuepeng, CHEN Qiang, Coal Combined Oil and Coal Chemical Industry, Northwest Coal, 2011, 9 (02): 77-82.