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ORIGINAL ARTICLE

Short-term safety risk assessment of CO_2 geological storage projects in deep saline aquifers using the Shenhua CCS Demonstration Project as a case study

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Abstract Although CO_2 geological storage has been recognized as an effective strategy to lower carbon emissions directly, there are no suitable guidelines for safety risk assessment of CO_2 geological storage projects in deep saline aquifers in China and elsewhere. When CO_2 is injected into deep saline aquifers, stratigraphic and structural trapping is the major basic mechanism controlling CO_2 storage capacity and migration in reservoirs. Therefore, a safety risk assessment method is proposed in this paper using perspectives from hydrogeological and environmental geology. The uncertainties and risks consist of CO_2 leakage, ground deformation, and induced earthquakes. Identifying and assessing potential risks are the first and most important step in the process of risk assessment. Based on the identification of risks of CO_2 geological storage projects, we built an elementary risk evaluation index system in an analytic hierarchy process framework. Meanwhile, the possibility of occurrence and damage to the environment and public caused by CO_2 leakage, ground deformation, and induced earthquakes was analyzed in detail, and current risk criteria were also summarized. Furthermore, using the Shenhua CO_2 Capture and Storage Demonstration Project as a case study, we performed a risk identification and evaluation by using qualitative or semi-quantitative methods in sequence, as well as developing the related preliminary risk management measures. This method and case study for short-term safety risk assessment could provide a guideline for site selection, injection design, and monitoring of CO_2 geological storage projects in deep saline aquifers.

Keywords CO_2 geological storage · Deep saline aquifer · Short-term safety risk · Risk identification · Risk evaluation

Introduction

CO_2 geological storage has been recognized as an effective strategy to lower carbon emissions directly. Twenty-three million tons of CO_2 are stored each year at eight large-scale integrated CO_2 Capture and Storage (CCS) Projects in the world, and this figure is expected to increase to over 36 million tons of CO_2 per year by 2015 (Global CCS Institute 2012).

There are several large-scale successful CO_2 geological storage projects in deep saline aquifers in the world. The first commercial-scale CO_2 geological storage project, the Sleipner Project operated by Statoil, removes CO_2 from natural gas and injects it into a saline formation under the North Sea. The Shenhua CCS Demonstration Project in the Ordos Basin of China sequesters 100,000 tons of CO_2 per year and is the largest coal-based full-chain CCS project in the world (Wu 2013). CO_2 can be injected into deep geological formations such as depleted oil and gas fields, coal beds, and saline aquifers (IPCC 2005). In contrast to CO_2 storage in deep saline aquifers, CO_2-enhanced oil recovery (CO_2-EOR) and coal bed methane (CO_2-ECBM) are CO_2

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geological utilization technologies, where part of the CO_2 is recovered during the project process. With the development of CO_2 geological storage projects in deep saline aquifers in China and elsewhere, potential safety risks, monitoring, and assessment has attracted increasing public attention, and has become a key research challenge (IPCC 2005; Bachu 2008). Intergovernmental Panel on Climate Change (IPCC 2005) presented potential environmental hazards and corresponding risks of CO_2 geological storage. Oldenburg (2008) developed a screening and ranking framework for CO_2 geological storage site selection based on health, safety, and environmental (HS&E) risk. Li et al. (2013) performed applied research on the Shenhua CCS Demonstration Project by using an improved framework. There are no laws or regulations in China suitable for risk assessment of CO_2 geological storage projects in deep saline aquifers. However, "Technical Guidelines for Environmental Risk Assessment on Projects" (*HJ/T169-2004*), developed by the Ministry of Environmental Protection of China, could provide a basic method for evaluation of CO_2 diffusion.

Risk is the probability or threat of damage, injury, liability, loss, or any other negative event that is caused by external or internal vulnerabilities, and that may be avoided through preemptive action. More formally, risk equates to the product of probability that some events will occur and the consequences of those events if they do occur (Stenhouse et al. 2009). Safety risk assessment is the identification and analysis of the dangerous and harmful factors existing in projects by using safety system engineering theory and methods and estimating the possibility and severity of events in order to propose safety precautions. In a broader context, risk assessment is simply an assessment of the safety of a specific event and the possible harmful consequences (Kaplan 1997), as shown in the following Formula (1):

$$R = P \times C, \tag{1}$$

where R is the evaluated value of the risk, P is the possibility of the potential risk event, and C is the harmful consequence of the risk event.

Therefore, using a hydrogeological and environmental geological approach and using information from comparative nuclear (Benson et al. 2005; Maul et al. 2007) and solid waste disposal projects (Ayomoh et al. 2008; Korucu and Erdagi 2012), a safety risk assessment method for CO_2 geological storage projects in deep saline aquifers has been developed, emphasizing risk identification of safety status and short-term evaluation. Furthermore, using the Shenhua CCS Demonstration Project as a case study, we performed risk identification and evaluation, and present preliminary risk management measures.

Risk identification

Identifying and assessing potential risks are the first major step in the risk assessment process. Risk identification relies on distinguishing various potential factors in sequence which could cause safety risk events and harmful consequences. The contribution of varying trapping mechanisms of CO_2 geological storage in deep saline aquifers at multiple time scales adds complexity to risk assessment. Once CO_2 is injected into geological formations underground, it can be trapped in the pore spaces by four main processes. The first process is stratigraphic and structural trapping. Another process is residual gas trapping, and Solubility trapping refers to CO_2 dissolving into the fluid of the geological formations, such as water. Finally, CO_2 can react with solid materials and become mineralized (Bachu et al. 1994; Baines and Worden 2004; IPCC 2005; Xu et al. 2005; Akbarabadi and Piri 2011; Liu 2012). However, because stratigraphic and structural trapping is the basic major mechanism (Davison et al. 2004) controlling CO_2 storage capacity and migration characteristic in saline aquifers and geological safety, risk identification should focus on the operational and short-term phase of CO_2 geological storage projects. Similarities can be found in radioactive waste disposal where performance assessment calculations must consider the return of radionucleotides to the accessible environment over periods longer than 10,000 years (Maul et al. 2007).

The objects of risk identification include injection facilities, risk materials, and risk categories. The risks of CO_2 geological storage have been analyzed to some extent for surface equipment to underground reservoirs (IPCC 2005; IEA 2008). Generally speaking, the uncertainties and risks are categorized as CO_2 leakage, ground deformation, and induced earthquakes.

The initiating risk events could be caused externally or internally in CO_2 geological storage projects. Risk events caused by earthquakes, active faults, tectonic ground fissures, fractures within caprocks, and abandoned deep wells around the CO_2 geological storage project site are considered external geological factors. However, unscientific injection design, operation violations, and other human-made factors could be considered internal factors.

CO_2 leakage

Supercritical CO_2 is less dense than water and tends to migrate to the top of reservoirs due to buoyancy. It is inevitable that the highly pressurized CO_2 will leak to some extent due to the permeable nature of the porous rocks, causing uncertainty in the storability of a reservoir (Xie and

Economides 2009). Abrupt leakage and gradual leakage are two different types of leakage scenarios (IPCC 2005).

Potential leakage pathways

The main potential leakage pathways are usually recognized are human-made, tectonic, leakage trough the caprocks, and hydraulic traps (IPCC 2005; Pruess 2008; Bachu and Celia 2009; Lemieux 2011). CO_2 may leak along anthropogenically created leakage pathways causing abrupt leakage. Injection, monitoring, and abandoned wells are recognized as potential leakage pathways due to poor or unknown conditions of cementing, alteration, abandonment, or plugging (Gasda et al. 2004; Carey et al. 2007).

Tectonic pathways include faults, fractures, ground fissures, and other tectonic leakage pathways created by earthquakes. Active faults are not only CO_2 leakage pathways, but also damage strata continuity, causing CO_2 leakage through the caprock. Meanwhile, tectonic ground fissures especially near active faults may become CO_2 leakage pathways near the surface. Appropriate site selection could avoid earthquakes and volcanoes, which are recognized as major factors for large-scale CO_2 leakage and global climate change. If CO_2 leaks along these tectonic pathways, it is usually difficult to manage.

CO_2 leakage through the caprock occurs when the capillary entry pressure threshold is reached. While the caprock may have the proper hydrogeological conditions for free phase CO_2 containment, fractures and faults can modify its integrity. These features may naturally exist but geomechanical damage can also occur when the yield strength of the caprock is exceeded by the pressure build-up created by the injection of CO_2 (Rutqvist and Tsang 2002; Rutqvist et al. 2007). A fourth potential escape pathway involves dissolved CO_2 that flows up-dip with regional groundwater flow. It is usually not considered because it is thought to take hundreds of thousands of years before the CO_2 reaches the atmosphere and it is expected that most CO_2 will precipitate before reaching the surface (Lemieux 2011).

Safety and environmental impacts of CO_2 leakage

The safety and environmental impacts of geological storage related to the risk of release of stored CO_2 fall into two broad categories (IPCC 2005): local environmental and safety impacts and global effects resulting from the release of stored CO_2 into the atmosphere. The features, processes, and mechanisms of all of the risk events are closely related to the impact and movement of injected CO_2 underground, and the risks of CO_2 leakage out of the storage complex, either to shallower formations or to the atmosphere (European Commission 2011).

Local environmental and safety impacts Damen et al. (2003) provided a detailed discussion of potential health, safety, and environmental risks and may be the first paper related to potential environmental impacts from geological CO_2 storage. Saripalli et al. (2003) presented perceived risks to humans and other species (e.g., trees and fish) associated with elevated levels of CO_2 in different media. Subsequently, much research has been performed on the environmental and safety effects of CO_2 geological storage, with a focus on CO_2 leakage.

CO_2 leakage to potable water aquifers can contaminate groundwater. CO_2 in a gas phase can dissolve partially or completely within fresh groundwater. CO_2 itself is not a concern to the water quality of an underground drinking water source, but it will change the geochemical conditions in the aquifers (Lemieux 2011). The dissolution of CO_2 in groundwater increases the total concentration of dissolved carbonate which in turn increases acidity and lowers the natural pH of groundwater (Langmuir 1997). Increased acidity can enhance the dissolution of minerals, including those containing hazardous trace elements (Zheng et al. 2009; Apps et al. 2010). Decreased pH could also mobilize hazardous trace elements adsorbed on clays, iron oxyhydroxides or the surface of other rock-forming minerals (Zheng et al. 2009; Apps et al. 2010). The resultant increase in concentration of hazardous trace elements can affect groundwater quality, possibly to the extent that safe drinking water limits are exceeded. However, in highly buffered aquifers, the potential for a pH decrease can be compensated by the dissolution of alkaline minerals like calcite (Bethke 2008). Under supercritical conditions, CO_2 is a highly effective solvent and capable of extracting contaminants from geologic materials such as polycyclic aromatic hydrocarbons. Those toxic compounds could be mobilized and could compromise water quality in nearby aquifers (Stevens et al. 2000).

Impacts of elevated CO_2 concentrations in the shallow subsurface could include lethal effects on plants and subsoil animals. High fluxes in conjunction with stable atmospheric conditions could lead to local high CO_2 concentrations in the air which could harm animals or people. Pressure build-up caused by CO_2 injection could trigger small seismic events (IPCC 2005).

Global environmental impacts CO_2 geological storage also has global environmental impacts, in that successful storage will reduce emissions from fossil fuel use and increase its potential as a greenhouse gas emission reduction option. In contrast, high-CO_2 release rates from storage sites would reduce the effectiveness of CO_2 geological storage projects.

Ground deformation

Essentially, the process of CO_2 injection exerts continuous pressure into reservoir rocks underground, increasing pore-fluid pressure, as well as the stress and volume of reservoir rocks. Because of a lower density and smaller coefficient of viscosity than saline water, a supercritical CO_2 plume will migrate driven by injection pressure and pore water buoyancy. The CO_2 plume with associated saline buoyancy and volume expansion force of reservoir rocks would transfer the overlying caprocks and cause deformation in the vertical direction. If the accumulated deformation is large enough, the shallow surface will uplift around the injection well, resulting in ground deformation.

The In Salah Gas project in Algeria involves injection of about 4,000 tons of CO_2 per day into the Krechba Carboniferous sandstone (a 20 m thick, methane producing reservoir) at a depth of 1,800 m near the Krechba gas field. The monitoring of injected CO_2, borehole surveys and geochemical, geophysical as well as geomechanical investigations are still underway. Because of a relatively deep reservoir, a relatively stiff overburden, and with the volume of CO_2 being injected fairly small compared to the overburden, the initial view of the In Salah Project was that no significant ground deformations would occur. However, InSAR data from the first few years of injection show a surface uplift on the order of 5–10 mm per year above active CO_2 injection wells and the uplift pattern extends several km laterally (Vasco et al. 2008a, b). The observed uplift can be explained by pressure changes and associated vertical expansion within the 20-m thick injection zone and the approximately 100-m thick zone of shaly sands immediately above the injection zone. Meanwhile, permeability at injection wells is strongly heterogeneous, affected by the degree of fracturing and perhaps by intersecting faults. Although the ground deformation in In Salah Gas project is a special case because of its sequestration characteristics, it still provides information valuable to all CCS projects.

Induced earthquakes

Deep-well injection of waste fluids may induce earthquakes with moderate local magnitudes (M_L), as in the 1967 Denver earthquakes (M_L of 5.3; Healy et al. 1968; Wyss and Molnar 1972) and the 1986–1987 Ohio earthquakes (M_L of 4.9; Ahmad and Smith 1988) in the United States. Seismicity induced by fluid injection likely results from increased pore-fluid pressure in the hypocentral region of the seismic event (Talebi et al. 1998). Microseismic data analysis together with interpretation of injection data at the In Salah CO_2 storage site provides a valuable tool for improved understanding of the subsurface injection and storage processes. More than 1,500 microseismic events have been detected semi-automatically between August 2009 and May 2012 and the occurrence of the events correlates clearly with increased injection rates and well-head pressures. Most likely the fracture pressure has been exceeded temporarily, resulting in a sudden increase of macroseisms (Oyea et al. 2013).

Once CO_2 injection-induced earthquakes occur near CO_2 geological storage project sites during implementation, it may damage infrastructure, including equipment for CO_2 injection, such as wellbores and monitoring devices. At the same time, the earthquakes may cause more public opposition to CO_2 geological storage projects. Large-scale CO_2 storage in deep saline aquifers may induce macroseisms. Therefore, scientific injection design is important to the success of projects.

Risk evaluation

Risk evaluation index system

The analytic hierarchy process (AHP) is an effective tool for dealing with complex decision making, and may aid the decision maker to set priorities and make the best decision (Saaty 1980; Saaty and Kearn 1985). It has been widely applied in risk or safety assessment because of its comprehensiveness and easy operability (Shi et al. 2009).

By reducing complex decisions to a series of pairwise comparisons, and then synthesizing the results, the AHP helps to capture both subjective and objective aspects of a decision, while at the same time reducing bias in the decision making process. The AHP considers a set of evaluation criteria, and a set of alternative options among which the best decision is to be made. It generates a weight for each evaluation criterion according to the decision maker's pairwise comparisons of the criteria. Higher weights indicate the higher importance of the corresponding criterion. For a fixed criterion, the AHP assigns a score to each option according to the decision maker's pairwise comparisons of the options based on that criterion. Higher scores indicate a better performance of the option with respect to the considered criterion. Finally, the AHP combines the criteria weights and the option scores, thus determining a global score for each option, and a consequent ranking. The global score for a given option is a weighted sum of the scores obtained with respect to all of the criteria.

Therefore, based on the risk identification of CO_2 geological storage projects and using information about CO_2 leakage, ground deformation, and induced earthquakes, we analyzed all of the risk factors in order to build an elementary risk evaluation index system using the AHP

Table 1 Elementary risk evaluation index system

Risk events	Risk factors
CO_2 leakage	Injection implementation
	Wellbore integrity and devices
	Geological safety conditions
	Mineral resources exploitation
Ground deformation	Simplified evaluation
Induced earthquakes	Simplified evaluation

framework (Table 1). The risk events for CO_2 geological storage projects in deep saline aquifers include CO_2 leakage, ground deformation, and induced earthquakes. The risk factors of risk events are injection implementation, wellbore integrity and devices, geological safety conditions, and mineral resource exploitation. However, our simplified evaluation used risk evaluation indexes for ground deformation and induced earthquakes only, because damage to the public and the environment for these two factors is more immediate than damage from CO_2 leakage.

Risk evaluation method

Occurrence probability of risk events

Although there are several demonstration or commercial CO_2 storage projects in deep saline aquifers, research on environmental impacts and safety risks is limited. We could only perform a risk evaluation by using qualitative or semi-quantitative methods. As is shown in Table 2 (Li et al. 2006), we transformed the qualitative descriptions of occurrence probabilities of risk events to quantitative values.

Table 2 Qualitative descriptions of occurrence probabilities and corresponding quantitative values

Qualitative descriptions	Probability magnitudes	Criteria
Absolutely sure	1	Definitely take place
Sure	0.2–0.9	Several similar events happened before
Highly possible	0.1	One event happened before
Possible	0.01	Similar events may occur without precautions
Unlikely	0.001	Happened elsewhere recently before
Very unlikely	1×10^{-4}	Happened elsewhere before
Highly unlikely	1×10^{-5}	Similar events occurred in record, but completely different
Almost impossible	1×10^{-6}	No similar events occurred in record

Damage degree classification of consequence of risk events

The risk evaluation set is the collection of possible consequences caused by risk factors. We can classify the degree of damage as a consequence of risk events and transform qualitative descriptions to quantitative values, by using relationships shown in Table 3 (Pruess 2008).

Risk calculation

Based on the transformed quantitative values of weights, occurrence probabilities, and damage degrees of risk factors, we could evaluate risk by using Formulas (1) and (2). Therefore, we could analyze potential risk events and maximum risk in order to make emergency precautions and avoid risk event occurrence.

$$R = \sum_{i=1}^{n} R_i A_i \quad (i = 1, 2, 3, \ldots, n), \tag{2}$$

where R is total evaluated risk, R_i is the evaluated risk of factor i, n is the number of risk factors, A is the weight of risk factors, and A_i is the weight of risk factor i.

Risk criteria

Acceptable risk criteria for individuals

Acceptable risk criteria for individuals indicate the risk level of people around the CO_2 geological storage project, with maximum and minimum values usually provided. The China Academy of Safety and Technology (2006) proposed acceptable risk criteria for individuals suitable for China based on study of the rules and regulations published by authoritative governments abroad (Table 4).

Individuals affected by risk events could be divided into three types (Table 4) based on sensitivity and population density. Values of tolerable and negligible risk per year for typical objects are recommended. The evaluated risk of CO_2 geological storage project in highly sensitive and high-population density areas should not be larger than 0.5×10^{-5} per year, but could be neglected if lower than 1×10^{-7} per year. Similarly, the largest tolerable risk per year in moderately sensitive and medium population density areas is 1×10^{-5}, and the largest negligible risk per year is 1×10^{-6}. The largest tolerable and negligible risk per year is 5×10^{-5} and 1×10^{-5}, respectively, in minimally sensitive and low-population density areas.

Acceptable risk criteria for the public

Acceptable risk criterion for the public is used to reduce accidental risks to the public. As shown in Fig. 1 (China

Table 3 Damage degree classification of consequence of risk events and corresponding quantitative values

Damage of degree	Quantitative value magnitude	Analogy	Acceptability
Extremely high	1×10^{-3}	Extremely dangerous operation	Unacceptable, immediate precautions should be taken
High	1×10^{-4}	Slightly dangerous operation	Corresponding precautions should be taken
Medium	1×10^{-5}	As dangerous as a swimming accident	Causing public attention, corresponding precautions should be taken
Low	1×10^{-6}	As possible as the probability of an earthquake occurrence	Causing no attention
Extremely low	1×10^{-7}	As possible as a meteorite falling	No one cares

Table 4 Object types affected by risk events and acceptable risk criteria for individuals

Object types	Typical objects	The largest tolerable risk per year	The largest negligible risk per year
Highly sensitive and high-population density areas	Government institutions, military control areas, cultural and historic spots, schools, hospitals, residential areas, large-scale stadiums and gymnasium	0.5×10^{-5}	1×10^{-7}
Moderately sensitive and medium population density areas	A few residents, labor intensive projects, small-scale stadiums and gymnasium	1×10^{-5}	1×10^{-6}
Minimally sensitive and low-population density areas	Technology intensive factories, parks and squares	5×10^{-5}	1×10^{-5}

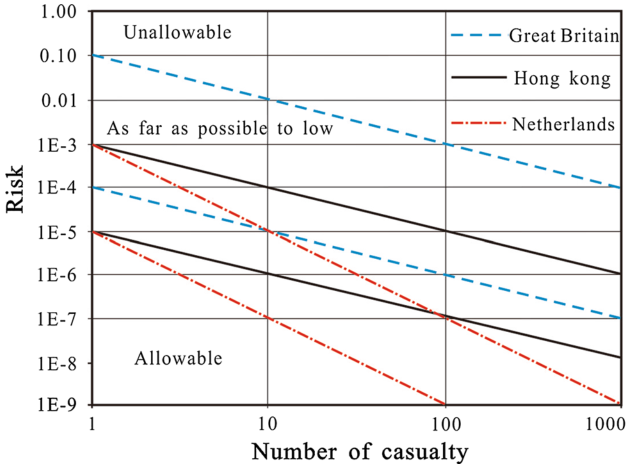


Fig. 1 Acceptable risk criteria for the public in the Netherlands, Great Britain, and Hong Kong

Academy of Safety and Technology 2006), two lines represent the maximum and minimum risks, respectively. The F–N graph provides acceptable, unacceptable, and ALARP areas of risk criteria for the public in the Netherlands, Great Britain, and Hong Kong.

Other risk criteria

The purpose of CO_2 geological storage projects is to reduce CO_2 emissions and project the earth's environment, so it is necessarily to develop risk criteria associated with CO_2 leakage, ground deformation, and induced earthquakes, which could provide more information for risk assessment in CCS projects.

Acceptable and limiting CO_2 leakage rates

While the goal of geological CO_2 storage is to store injected CO_2 underground permanently, there are likely to be projects where some CO_2 leakage occurs. Acceptable rates of leakage in the past have been expressed as a percentage of the total volume injected and typically range from 0.01 % per year (1 % over 100 years) to 0.001 % per year (1 % over 1,000 years) (Bowden and Rigg 2005; Shuler and Tang 2005). For a CO_2 storage site which annually releases 0.001 of the amount stored, effectiveness is around 60 % after 1,000 years. This rate of release would be equivalent to a fraction retained of 90 % over 100 years or 60 % over 500 years. It is likely that, in practice, geological and mineral storage would have lower rates of release than this and hence higher effectiveness—for example, a release rate of 0.01 % per year would be equivalent to a fraction retained of 99 % over 100 years or 95 % over 500 years (IPCC 2005).

The performance assessment carried out during Phase 1 of the IEA WeyburnCO_2 Monitoring and Storage Project focused on the capabilities of the reservoir to contain the injected CO_2 (IEA GHG 2008). In terms of the expected evolution of the storage system (Base Case) and possible

CO_2 migration via natural leakage pathways, the geology would keep the CO_2 underground for at least 5,000 years. In terms of human-made pathways (abandoned wells), a small amount of leakage was predicted over 5,000 years, with the mean value for maximum leakage rate (for several hundred wells) of 4×10^{-4} kg/day, with 95 % of the simulations yielding a value $<1.6 \times 10^{-3}$ kg/day (Zhou et al. 2005).

CO_2 concentration

Rice (2013) suggested that CO_2 concentrations in the range of 0.5–1.5 % are well tolerated by healthy humans, and "prolonged exposure to CO_2 concentrations of 1 % may significantly affect health on the general population." (A limit of 0.35 % CO_2 in indoor air is recommended by Health Canada).

CO_2 is not considered as a pollutant in the current legal system of China; however, the "Occupational exposure limits for hazardous agents in the work place—Chemical hazardous agents" (*GBZ 2-2002*) enacted by the National Health and Family Planning Commission of China states that CO_2 concentration exposure should not be larger than 18,000 mg/m^3 for a short time. "Indoor air quality standard" (*GB/T18883-2002*) also enacted by the National Health and Family Planning Commission of China recommends the indoor average CO_2 concentration of 0.1 %.

Case study

Risk identification and engineering analysis

The Shenhua CCS Demonstration Project is the first CCS project in the Ordos Basin of China, and is the largest coal-based full-chain project of CO_2 capture and geological storage in deep saline aquifers in the world. There is a single injection wellbore called the Zhongshenzhu 1# wellbore and two monitoring wells called the Zhongshenjian 1# and Zhongshenjian 2#. A total of 167 kilo-tons of CO_2 was injected into the deep saline aquifers of Mesozoic sandstone and Paleozoic Majiagou carbonate rocks from September 2011 to November 2013 (Wang 2013).

Shenhua CCS Demonstration Project is located in the northeast of Yimeng uplift of Ordos Basin. 3D seismic exploration (Fig. 2) and drilling data (Fig. 3) show that the formations are sloping from northeast to southwest slowly at the dip, around 1° as a gentle southward monoclinal structure (Wu 2013; Guo et al. 2014; Wei et al. 2014). And the stratigraphy sequences from bottom to top are as follows: Lower Ordovician Majiagou Formation (O_1m); Middle Carboniferous Benxi Formation (C_2b) and Upper Carboniferous Taiyuan Formation (C_3t); Lower Permian Shanxi Formation (P_1s), Lower Permian Shihezi Formation (P_1sh), Upper Permian Shiqianfeng Formation (P_2sh); Lower Triassic Liujiagou Formation (T_1l) and Heshanggou Formation (T_1h), Middle Triassic Zhifang Formation (T_2z), Upper Triassic Yanchang Formation (T_3y); Lower Jurassic Yan'an Formation (J_1y), Middle Jurassic Zhiluo Formation (J_2z) and An'ding Formation (J_2a); Lower Cretaceous Dongsheng-Luohandong Formation ($K_1^{d\text{-}l}$); Quaternary (Q).

Using data from geological surveys, 3D seismic exploration, drillings, and numerical modeling, risk identification and engineering analysis were performed as follows.

Potential leakage pathways and damage

Injection operation To date, the Shenhua CCS Demonstration Project runs well, with monitoring showing no CO_2

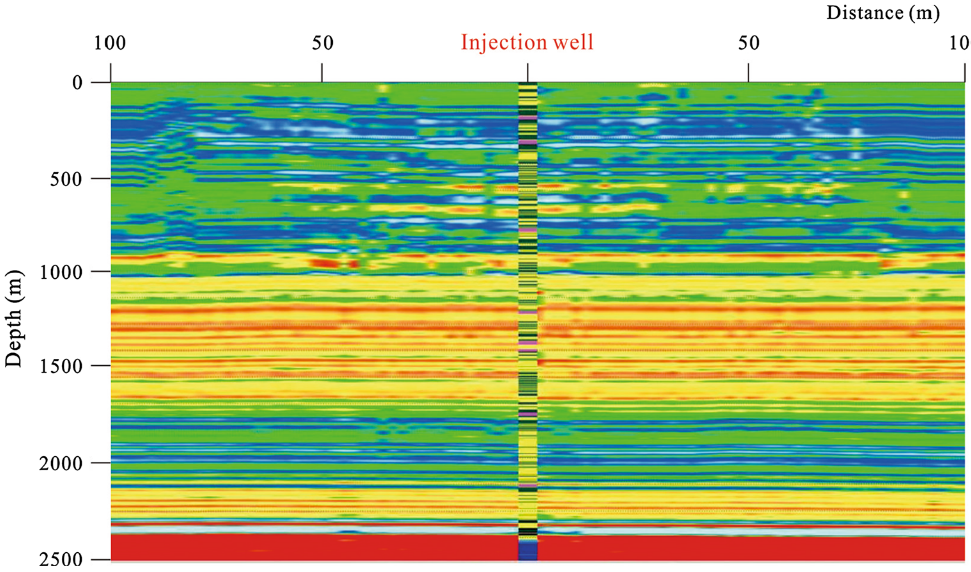


Fig. 2 Typical profile of 3D vertical seismic profiling (VSP) seismic exploration

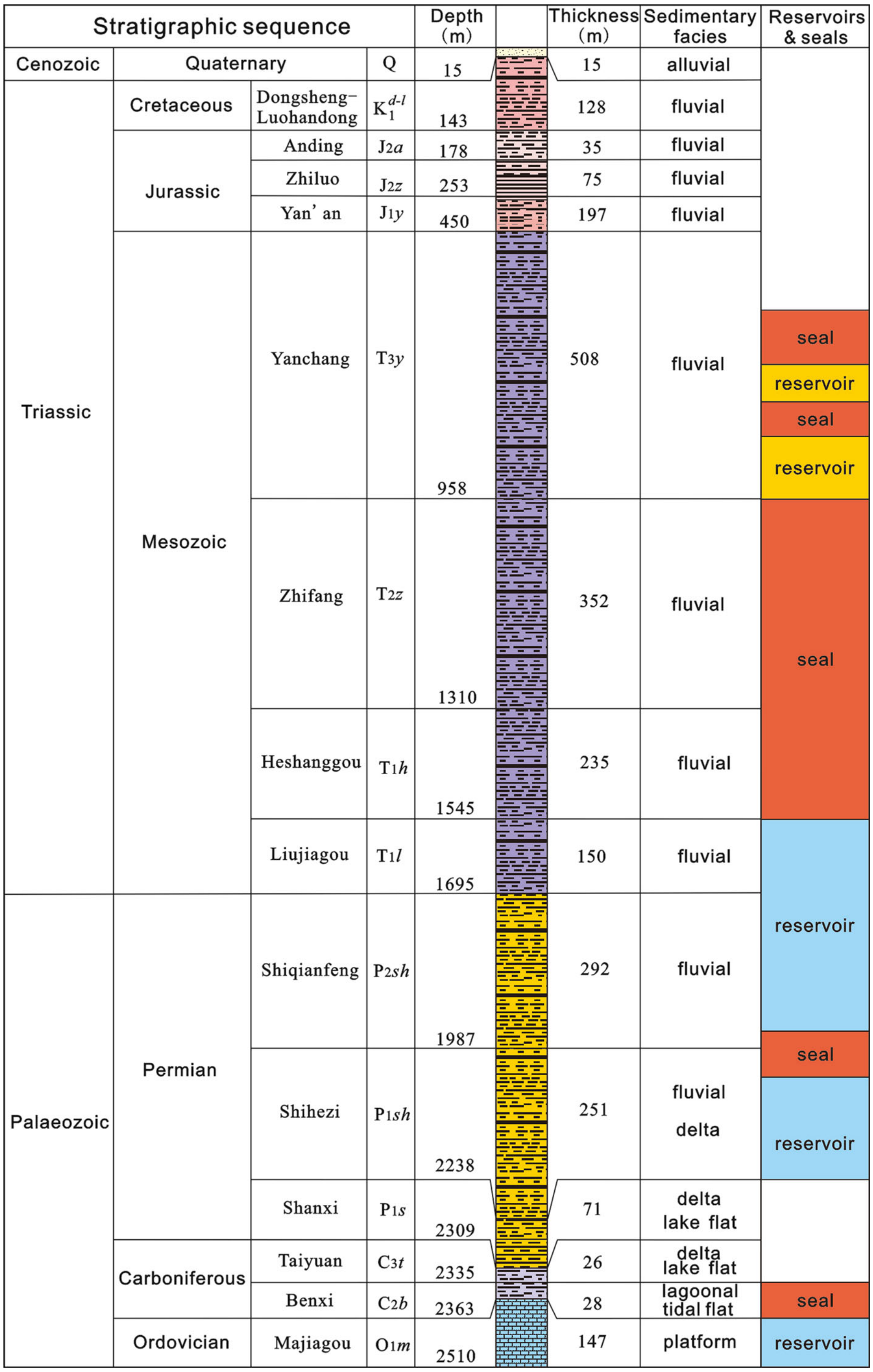


Fig. 3 Reservoir-seal assemblages of the Shenhua CCS Demonstration Project

leaks or related environmental hazards (Li et al. 2013). As the first deep saline aquifer demonstration project, the Shenhua CCS project operates under scientific management regulations, and has made emergency precautions in order to avoid potential risk event occurrence and damage.

Wellbore integrity and devices The injection and monitoring wellbores were constructed strictly in accordance with related rules, and monitoring results suggested that devices run well. CO_2 leakage along this kind of leakage pathways is a low possibility.

Geological safety Historical earthquakes: The peak ground acceleration of the tectonic area in which the Shenhua CCS Demonstration Project is located is 0.05 g, and the basic seismic intensity is VI. Only a few small earthquakes occurred near the injection site with no earthquake disasters on record, and the crust is stable.

Fracture structures and activity: Data from a ground geological survey and 3D seismic exploration show no active faults near the project site. Although there are several structural fractures developing shallowly, the fault throws are small and no faults are found near the Zhongshenzhu 1# well. There are no obvious fractures in the core samples from the injection well.

Sealing capacity: We identified three main regional caprocks in the Shenhua CCS Demonstration Project, including the Benxi Formation mudstone, the upper part of Shihezi Formation and lower part of Shiqianfeng Formation mudstone, and the Heshanggou and Zhifang Formation mudstone, with large thickness, good continuity, and sealing ability (Fig. 3). Furthermore, if CO_2 breaks through the middle part of the Zhifang Formation, which is the most important regional mudstone seal as mentioned above, there are two reservoir-seal assemblages below 800-m depth which could provide buffering—the upper part of Zhifang Formation sandstones—top of Zhifang Formation mudstones and the bottom of the Yanchang Formation sandstones and mudstones above. The monitoring data of the Zhongshenjian 2# wellbore, the bottom of which is above all the reservoirs, show no CO_2 breakthrough of the Heshanggou and Zhifang Formation mudstone. Compared with the caprocks of CO_2 gas fields in Lishui Sag of the East China Sea Shelf Basin, where the influence thickness in the vertical direction is <10 cm because of corrosion of supercritical CO_2 on carbonate minerals, the major caprocks of Shenhua CCS Demonstration Project should provide effective sealing for injected CO_2.

However, although the 3D seismic exploration (Fig. 2) and drillings (Fig. 3) show that the mudstone continuity in the major caprocks is sound (Wu 2013; Li et al. 2013; Guo et al. 2014), the fluvial depositional environment of Mesozoic strata and heterogeneity could not ensure that there is no possibility of CO_2 breakthrough of caprocks.

Tectonic ground fissures: The topographic change activities are relatively small in general, and there are no tectonic ground fissures near the injection well.

Hydrodynamic condition: The reservoirs of the Shenhua CCS Demonstration Project involve two aquifer systems, which are Cambrian-Ordovician carbonate saline aquifers and Carboniferous-Jurassic sandstone saline aquifers. Both of them mainly accept surface water and shallow groundwater recharge flowing along the dip direction from the east to the center of the Ordos Basin. Therefore, the hydrodynamic condition could play a prominent part in blocking the CO_2 plume from migrating to the east, which is suitable for CO_2 geological storage. Liu et al. (2013) used the ECO_2N module of TOUGH2 to simulate flow and pressure configurations in response to small-scale CO_2 injection into multilayer saline aquifers, and the results showed that the lateral distance reached by the CO_2 plume was limited to within a radius of 200 m from the injection point, and its vertical movement was restricted by the low permeability siltstone and mudstone layers. Generally speaking, the distance of CO_2 migration in the lateral direction driven by hydrodynamic force and injection pressure is limited. The CO_2 plume should not reach faults below 1,000 m underground around the Zhongshenzhu 1# well.

Geological hazards: landslide, mudflow, and rockfall were not found in Shenhua CCS Demonstration Project site by ground geological survey, suggesting the site is suitable for engineering construction.

Mineral resources exploitation There was no abandoned well identified by the geological survey data within 100 m. The Shenhua CCS Demonstration Project is located in the coal pillar of the Yan'an Formation at a depth of 400 m. About 10 km away from the Shenhua CCS Demonstration Project in the east, the nearest ground subsidence area induced by coal mining is obvious. Therefore, together with coal mining, subsidence may threaten the safety of injection and monitoring wells, which could cause CO_2 leakage.

Ground deformation

Numerical stimulation Li (2012) established a coupling analysis model for the Shenhua CCS Demonstration Project considering hydraulic field and pressure field, and

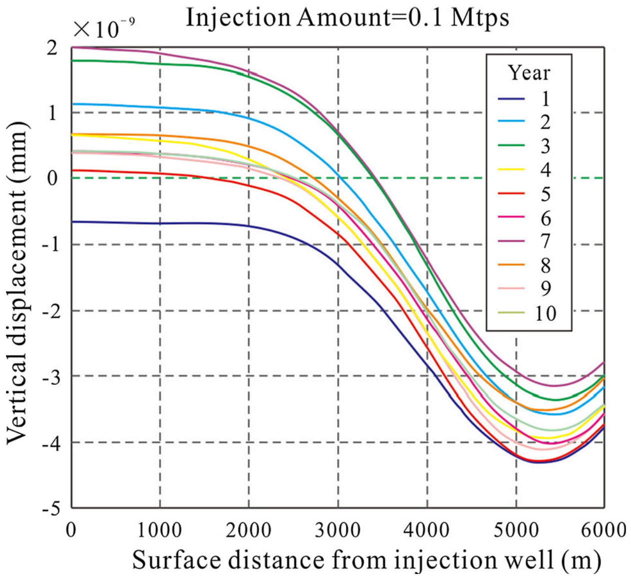


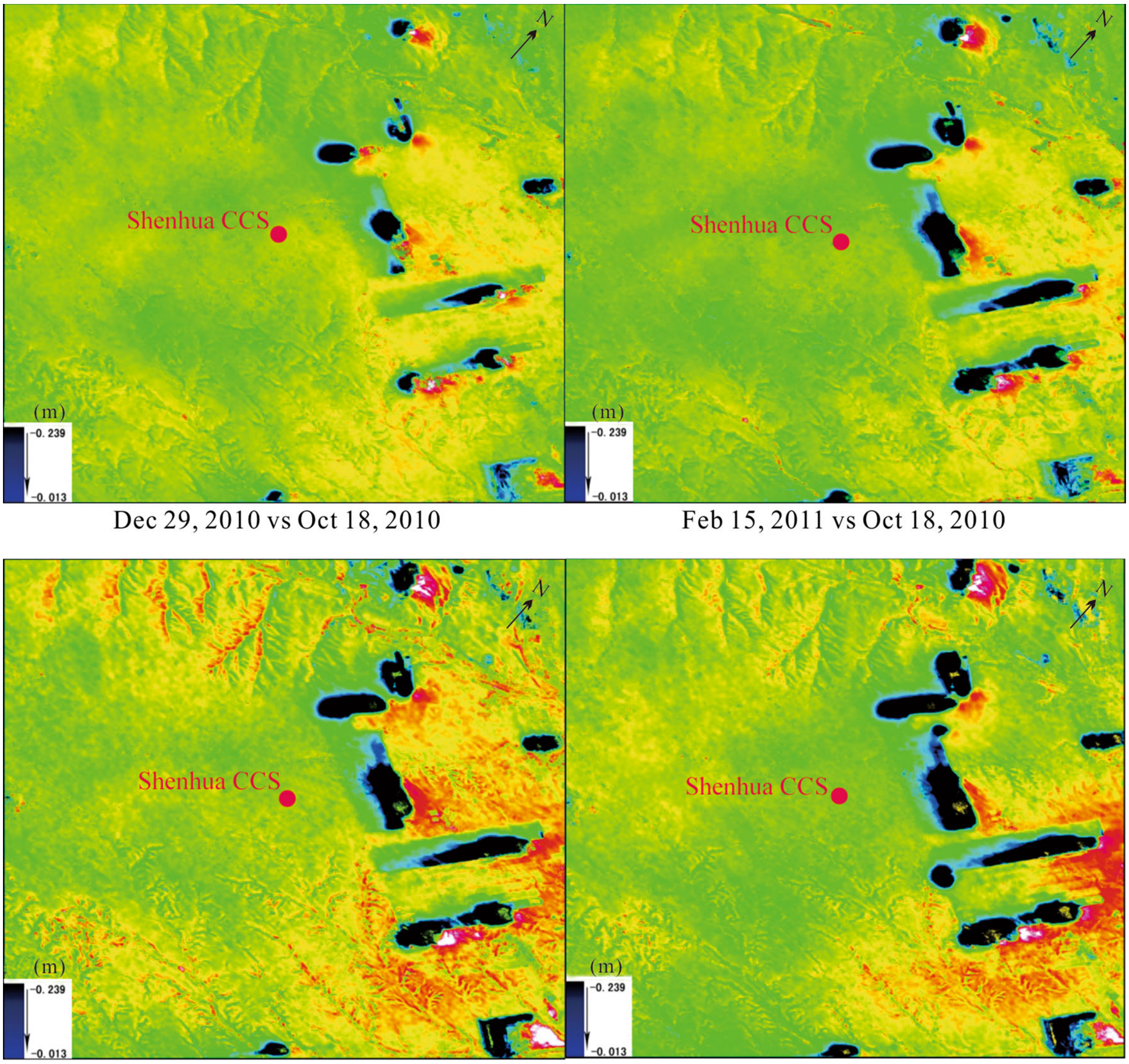
Fig. 4 Numerical simulation results for ground deformation based on hydraulic and pressure fields

performed a numerical simulation based on the Biot equation (Biot 1941). The numerical simulation result is shown in Fig. 4, we could conclude that the ground deformation in the Shenhua CCS Demonstration Project site was small and difficult to discern in the first 10 years. Although ground deformation is more and more obvious along with continuous CO_2 injection from the first to tenth years, the maximum deformation displacement in the vertical direction is $<5 \times 10^{-9}$ mm. Ground deformation displacement near the injection well is affected by project construction, but CO_2 injection into deep saline aquifers subjected the ground to uplift overall. However, surface subsidence occurs 3,000–5,000 m away from the injection well as well, but is not obvious.

Monitoring using D-InSAR technology As one of the key members in the Shenhua CCS group, China geological survey center for hydrogeology and environmental geology (CHEGS) has carried out ground deformation monitoring four times using D-InSAR technology from 2010 to 2011. There are ten obvious ground deformation areas, with the nearest one being 10 km away from the injection well and there is no obvious ground deformation in the Shenhua CCS Demonstration Project site (Fig. 5). The ten obvious ground deformation areas are mainly caused by coal mining which has been confirmed by geological survey.

Induced earthquakes

Based on geological analysis, many researchers (Wu 2013; Guo et al. 2014) evaluated the CO_2 geological storage potential by numerical simulation in Shenhua CCS Demonstration Project. And all the results suggested that the reservoirs in the Shenhua CCS Demonstration Project site



Dec 29, 2010 vs Oct 18, 2010

Feb 15, 2011 vs Oct 18, 2010

Mar 11, 2010 vs Oct 18, 2010

Apr 28, 2011 vs Oct 18, 2010

Fig. 5 Ground deformation monitoring using D-InSAR technology could handle 10 × 10^4 t/a of CO_2 geological storage per single injection well for 3 years. After 167 kilo-tons of CO_2 injected, Liujiagou sandstone reservoir becomes the most effective reservoir with the largest capacity without hydraulic fracturing. It has stored over 90 % of the CO_2 injected, which reflects the superiority of sandstone saline aquifers for CO_2 geological storage (Wang 2013). Therefore, there is still much potential space for CO_2 geological storage, without any felt earthquakes before.

Meanwhile, because of discontinuous captured CO_2 production from Shenhua coal to liquid and chemical factory and the safety of reservoirs, the injection rates are kept low. Although monitoring for small seismic events has not been conducted before, the rational CO_2 injection rate and pressure could ensure that induced earthquakes will not be likely to occur.

Risk evaluation

Risk calculation

Weight evaluation Comprehensively considering the geological survey, injection, monitoring, and numerical simulation results of the Shenhua CCS Demonstration Project in risk identification mentioned above, we improved the risk evaluation index system outlined in Table 1, as illustrated in Table 5. The hierarchy model was classified into four layers, i.e., goal layer, level 1 criterion layer, level 2 criterion layer, and level 3 criterion layer. The goal is to evaluate the risk of Shenhua CCS Demonstration Project. At level 1, there exist three evaluation criteria which are risk events of CO_2 leakage, ground deformation, and induced earthquakes. However, ground deformation and induced earthquakes were simplified to evaluate the corresponding risk. At level 2, CO_2 leakage in turn consists of injection implementation, wellbore integrity and devices, geological safety conditions, and mineral resources exploitation. At level 3, injection implementation consists of overlarge injection design and irregular operation. Similarly, we can classify the risk events, risk factors, and sub risk factors in different levels.

Taking into account the contribution of each risk factor to risk size of each corresponding risk event, and the contribution of each event to total risk, we calculated the weights of risk factors using AHP in the following four steps (Saaty 1980, 1985; Spires 1991; Abdullah et al. 2013).

Step 1 Construct the hierarchical structure and obtain normalized matrix.
First, the criteria are compared with respect to the goal. $(a_{ij})n \times n$ matrix, denoted as A, is created using the pairwise comparisons with the elements a_{ij} indicating the value of criterion i relative to criterion j, as shown in the following Formula (3).

$$A = \begin{bmatrix} a_{11} & a_{12} & a_{13} & \cdots & a_{1n} \\ a_{21} & a_{22} & a_{23} & \cdots & a_{2n} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ a_{n1} & a_{n2} & a_{n3} & \cdots & a_{nn} \end{bmatrix}_{n\times n} \tag{3}$$

The values a_{ij} are obtained by the $a_{ii} = 1$, $a_{ij} = 1/a_{ji}$, where $a_{ij} > 0$, for all i. Therefore, if a number is assigned to element i when compared to element j, then j has the

Table 5 Index system for risk evaluation of Shenhua CCS Demonstration Project

Risk events	Weights (W)	Risk factors	Weights (W)	Sub risk factors	Weights (W)
CO_2 leakage (a)	0.61	Injection implementation (a_1)	0.07	Overlarge injection design (a_{11})	0.70
				Irregular operation (a_{12})	0.30
		Wellbore integrity and devices (a_2)	0.31	Zhongshenzhu 1# well and devices (a_{21})	0.57
				Zhongshenjian 1# well and devices (a_{22})	0.29
				Zhongshenjian 2# well and devices (a_{23})	0.14
		Geological safety conditions (a_3)	0.51	Earthquake hazards (a_{31})	0.38
				Active faults damage (a_{32})	0.25
				Fault structures (a_{33})	0.15
				CO_2 breakthrough the caprocks (a_{34})	0.10
				Tectonic ground fissures (a_{35})	0.06
				Hydraulic diffusion (a_{36})	0.04
				Geological disasters on the ground (a_{37})	0.02
		Mineral resources exploitation (a_4)	0.11	Abandoned wells (a_{41})	0.30
				Coal mining (a_{42})	0.70
Ground deformation (b)	0.12	Simplified evaluation			
Induced earthquakes (c)	0.27	Simplified evaluation			

reciprocal value when compared with i. Second, its entries are normalized by dividing them by their sum. This is repeated for all columns to obtain the normalized matrix A (A_{norm}) as follows.

$$A_{\text{norm}} = \begin{bmatrix} a_{11}/a'_1 & a_{12}/a'_2 & a_{13}/a'_3 & \cdots & a_{1n}/a'_n \\ a_{21}/a'_1 & a_{22}/a'_2 & a_{23}/a'_3 & \cdots & a_{2n}/a'_n \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ a_{n1}/a'_1 & a_{n2}/a'_2 & a_{n3}/a'_3 & \cdots & a_{nn}/a'_n \end{bmatrix}_{n \times n}, \tag{4}$$

where a_{ij} in the above matrix is the pairwise comparisons of ith row relative to ith column, a'_n is the sum of the pairwise comparisons in the ith column.

Step 2 Find the criteria weight and geometric means of $\sqrt[n]{\mu_i}$, respectively.

$$\sum_{i=1}^{n} \mu_i = \sum_{i=1}^{n} \sum_{j=1}^{n} a_{ij} \tag{5}$$

Step 3 Find the eigenvector by normalized the pairwise comparisons, and calculate the weights (W) in different level layers.

$$W_i = \frac{\sqrt[n]{\mu_i}}{\sum_{i=1}^{n} \mu_i} \tag{6}$$

Step 4 Check the consistency ratio (CR), the comparison matrix will be considered to be consistent if there exist CR < 1.

Calculate the maximal latent root $\lambda_{\max}$.

$$\lambda_{\max} = \sum_{i=1}^{n} \frac{(AW)_i}{nW_i} \tag{7}$$

Calculate the coincidence indicators (CI)

$$\text{CI} = \frac{\lambda_{\max} - n}{n - 1} \tag{8}$$

Check the CR. The CR is consistent when its value is <0.1.

$$\text{CR} = \text{CI}/\text{CR} \tag{9}$$

When RI is the random index and depends on the number of element being compared, n and takes on the values are shown in Table 6.

Risk calculation Based on Tables 2 and 3, we evaluated the occurrence probabilities and degree of damage of all risk factors to give corresponding quantitative values.

Finally, we performed the risk calculation by using Formula (10) improved from Formula (1) and Formula (2), and the detailed risk values are shown in Table 7.

$$\begin{aligned} R &= R_a \cdot W_a + R_b \cdot W_b + R_c \cdot W_c = \sum_{i=1}^{4} R_{a_i} \cdot W_{a_i} \\ &\quad + P_b \cdot C_b \cdot W_b + P_c \cdot C_c \cdot W_c \\ R_{a_{ij}} &= \sum_{j=1}^{m} P_{a_{ij}} \cdot C_{a_{ij}} \cdot W_{a_{ij}} \\ &\quad (j = 1, \ldots, m;\ m \text{ is the number of sub factors}) \end{aligned} \tag{10}$$

where R is the total evaluated risk, R_a is the evaluated risk of CO_2 leakage, R_b is the evaluated risk of ground deformation, R_c is the evaluated risk of induced earthquakes, R_{a_i} is the risk of factor i, $R_{a_{ij}}$ is the risk of sub factor ij, P_b is the occurrence probability of ground deformation, P_c is the occurrence probability of induced earthquakes, P_{ij} is the occurrence probability of sub factor ij, W_a is the weight of CO_2 leakage, W_b is the weight of ground deformation, W_c is the weight of induced earthquakes, W_{a_i} is the weight of factor i, $W_{a_{ij}}$ is the weight of sub factor ij, C_b is the harmful consequence of ground deformation, C_c is the harmful consequence of induced earthquakes, and $C_{a_{ij}}$ is the harmful consequence of sub factor ij.

Risk analysis

Inferred by the analysis on the quality of the reservoir, geological safety, and public and environmental conditions, the Shenhua CCS Demonstration Project is suitable for CO_2 geological storage. Based on the object types affected by risk events and the acceptable risk criteria for individuals (Table 4) and acceptable risk criteria (Fig. 1), we can conclude that the total evaluated risk of the Shenhua CCS Demonstration Project is 6.47E−8, which is within the allowable range for the public and could be negligible for individuals.

As shown in Table 7, the possible maximum risk event is CO_2 leakage, and the most likely risk factor is mineral resource exploitation, as ground deformation or ground

Table 6 The value of RI

阶数	1	2	3	4	5	6	7	8	9	10	11	12
取值	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.46	1.49	1.52	1.54

fissures caused by coal mining may damage the integrity of injection and monitoring wellbores and devices. In addition, the risk of CO_2 breakthrough of the caprocks, causing leakage, should be given more attention by all CO_2 geological storage projects as well.

Table 7 Risk calculation result of the Shenhua CCS Demonstration Project

Total risk (*R*)	Risk events	Risk (*R*)	Risk factors	Risk (*R*)	Sub risk factors	Probability (*P*)	Consequence (*C*)	Sub risk (*R*)
6.47E−8	CO_2 leakage (*a*)	1.06E−7	Injection implementation (a_1)	3.07E−9	Overlarge injection design (a_{11})	1×10^{-6}	1×10^{-4}	1E−10
					Irregular operation (a_{12})	0.001	1×10^{-5}	1E−8
			Wellbore integrity and devices (a_2)	6.13E−8	Zhongshenzhu 1# well and devices (a_{21})	1×10^{-4}	1×10^{-3}	1E−7
					Zhongshenjian 1# well and devices (a_{22})	1×10^{-4}	1×10^{-5}	1E−8
					Zhongshenjian 2# well and devices (a_{23})	1×10^{-4}	1×10^{-5}	1E−8
			Geological safety conditions (a_3)	1.98E−8	Earthquake hazards (a_{31})	1×10^{-5}	1×10^{-3}	1E−8
					Active faults damage (a_{32})	1×10^{-6}	1×10^{-3}	1E−8
					Fault structures (a_{33})	1×10^{-6}	1×10^{-3}	1E−8
					CO_2 breakthrough the caprocks (a_{34})	0.01	1×10^{-5}	1E−7
					Tectonic ground fissures (a_{35})	1×10^{-6}	1×10^{-4}	1E−10
					Hydraulic diffusion (a_{36})	1×10^{-5}	1×10^{-6}	1E−11
					Geological disasters on the ground (a_{37})	0.01	1×10^{-5}	1E−7
			Mineral resources exploitation (a_4)	7E−07	Abandoned wells (a_{41})	1×10^{-6}	1×10^{-4}	1E−10
					Coal mining (a_{42})	0.01	1×10^{-4}	1E−6
	Ground deformation (*b*)	1E−11	Simplified evaluation			1×10^{-5}	1×10^{-6}	1E−11
	Induced earthquakes (*c*)	1E−10	Simplified evaluation			1×10^{-6}	1×10^{-4}	1E−10

Risk management

Improve the quality of injection

Injection pressures, potentials, and rates that are too large may cause risk, even in abandoned reservoirs. More numerical simulation and injection tests are needed to better guide CO_2 injection. Meanwhile, workers should implement injection methods strictly according to current scientific information and management regulations in order to avoid human-made risk events.

Improving monitoring

Because CO_2 migration characteristics are affected by geological conditions, monitoring of the CO_2 plume in the subsurface is important to the success of the project, providing key data for effectiveness, safety, and continuity of the sequestration project. Monitoring should be improved to identify risk and possible CO_2 leakage pathways. Tracking the distribution of trapped CO_2 in the fluid, dissolved and solid phases are needed for plume confirmation, leakage detection, and regulatory oversight. Existing monitoring methods include well testing and pressure monitoring, use of chemical tracers, chemical sampling, surface and borehole seismic analysis, electromagnetic, and other geotechnical instruments (Benson and Myer 2002; Klara et al. 2003; Sato 2006; Saito et al. 2007; Loizzo et al. 2011; Wiese et al. 2013; Eshiet and Sheng 2014). The spatial and temporal resolution of current methods is unlikely to be sufficient for confirmation of performance and leakage detection. Remote sensing requires high-resolution mapping techniques, such as Interferometric Synthetic Aperture Radar (InSAR) (Pritchard et al. 2014; Ramirez and Foxall 2014), for tracking migration of sequestered CO_2 and its by-products as well as deformation and microseismicity monitoring (Rutqvist et al. 2009).

Taking precautions

The purpose of CO_2 geological storage is to reduce CO_2 emissions and slow climate change. If large risk events occur, remedy methods should be performed to lower or avoid damage. Precautions should be taken in the early stage of CCS project implementation, and should be accepted by experts and the public.

While there is limited experience with geological storage, closely related oil industrial experience, nuclear (Benson et al. 2005; Maul et al. 2007) and solid waste disposal research (Ayomoh et al. 2008; Korucu and Erdagi 2012) could serve as a basis for appropriate risk management, including remediation. The effectiveness of the available risk management methods still needs to be demonstrated for use with CO_2 storage. If leakage occurs at a storage site, remediation to stop the leakage could involve standard well-repair techniques or the interception and extraction of the CO_2 before it would leak into a shallow groundwater aquifer (IPCC 2005).

Conclusions

As an environmental project to reduce greenhouse gas emissions, safety risk assessment of CO_2 geological storage projects in deep saline aquifers should consider risk events including CO_2 leakage, ground deformation, and induced earthquakes. In this paper, a safety risk assessment method, based on hydrogeology and environmental geology information, is proposed, emphasizing the risk identification of safety status and short-term evaluation. Although the method is only based on qualitative or semi-quantitative information, it can be used to preliminarily assess whether the selected site for a project is suitable. Using the Shenhua CCS Demonstration Project as a case study, risk identification of potential leakage pathways could provide a site selection framework. However, more numerical simulations and experiments need to be used to improve occurrence probabilities of risk events. Additionally, damage to the environment and the public caused by risk events should be further studied in comparison to natural CO_2 emissions, such as Mammoth Mountain in California and Nyos Lake in Cameroon. Furthermore, the criteria of risk events are vitally important for CCS projects in regard to CO_2 emissions, and risk assessment methods should be in accordance with any laws and regulations.

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