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Analysis of Caprock Mechanical Stability for CO_2 Geological Storage Based on the Fuzzy Analytic Hierarchy Process

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Abstract: ***Carbon dioxide geological sequestration (CCS) technology is a key measure for addressing climate change, and its safety heavily depends on the mechanical stability of the caprock in the storage formation. This paper develops a comprehensive evaluation system based on the Fuzzy Analytic Hierarchy Process (FAHP) to assess the mechanical stability of the caprock after CO_2 injection into saline aquifers. Compared to other quantitative evaluation methods, FAHP is more effective at handling the fuzziness and uncertainty inherent in the evaluation process. By utilizing a fuzzy judgment matrix, it accurately reflects the relative importance and uncertainty of various factors, thus enhancing the scientific rigor and reliability of the evaluation results. To validate the effectiveness of this evaluation system, an engineering case study was conducted using geological data from the Jilin Oilfield. The results indicate that the caprock of the Fourth Member of the Sifangtai Formation in the Jilin Oilfield, as evaluated by the FAHP model, exhibits high stability across multiple mechanical indicators, and possesses strong CO_2 sequestration capacity in terms of thickness, compressive strength, shear strength, and low permeability. The evaluation result was classified as "Good, " meeting the safety requirements for CO_2 sequestration. This study demonstrates the advantages of FAHP in assessing the mechanical stability of caprocks in complex geological environments and provides an effective evaluation tool and technical support for CO_2 sequestration projects in the Jilin Oilfield and similar regions. In the future, integrating actual monitoring data to further optimize this evaluation system will provide more accurate decision-making support for the long-term stability prediction and risk management of CO_2 sequestration.***

Keywords: Carbon Dioxide Geological Sequestration, Caprock Mechanical Stability, Fuzzy Analytic Hierarchy Process (FAHP).

1. Introduction

As global climate change and greenhouse gas emissions continue to intensify [1, 2], Carbon Capture and Storage (CCS) has gained widespread attention worldwide [3]. CCS technology involves injecting CO_2 captured from industrial activities deep underground into storage reservoirs, where it is securely stored to prevent its release into the atmosphere, thereby mitigating the greenhouse effect [4]. However, the long-term safety of CO_2 sequestration heavily depends on the mechanical stability of the caprock, as its integrity determines the effectiveness of CO_2 storage.

Currently, numerous studies have been conducted on the stability of caprocks during CO_2 sequestration, covering areas such as numerical simulation, experimental analysis, and evaluation systems based on Analytic Hierarchy Process (AHP) [5]. However, traditional evaluation methods often face limitations when addressing complex, multi-layered, and multi-factor systems, particularly in dealing with issues of uncertainty and fuzziness [6]. These limitations may lead to misassessments of sequestration safety, thereby failing to effectively prevent potential CO_2 leakage risks.

To address the aforementioned issues, the Fuzzy Analytic Hierarchy Process (FAHP), an advanced decision-making method, introduces fuzzy mathematical theory, allowing for better management of the uncertainty and complexity inherent in the evaluation process [7]. Therefore, applying FAHP to the comprehensive evaluation of caprock mechanical stability during CO_2 sequestration is of significant importance. This approach not only reflects the overall stability of the caprock through multi-factor and multi-level weight analysis, but also more effectively quantifies the impact of various uncertainty factors on the evaluation results.

This paper aims to develop a systematic evaluation framework for caprock mechanical stability based on FAHP, with a particular focus on the mechanical effects of CO_2 injection into saline aquifers. By establishing a multi-level, multi-indicator evaluation framework and utilizing fuzzy judgment matrices and membership functions, this paper proposes a new comprehensive evaluation method for caprock mechanical stability in CCS technology. The development of this evaluation system not only facilitates the accurate assessment of the long-term safety of CO_2 sequestration but also provides a scientific basis for the site selection and design of future carbon sequestration projects.

2. Establishment of an Evaluation System for Caprock Mechanical Stability

The evaluation of caprock mechanical stability in CO_2 geological sequestration is a complex, multi-factorial, and multi-level problem, involving various aspects such as rock mechanics, stress state, geological structure, and injection conditions [8]. To accurately assess the mechanical stability of the caprock after CO_2 injection into saline aquifers, this paper constructs an evaluation index system based on the Fuzzy Analytic Hierarchy Process (FAHP). The system applies the Analytic Hierarchy Process (AHP) to assign weights to different indicators, enabling a quantitative and intuitive analysis of caprock mechanical stability.

2.1 Concept of caprock Mechanical Stability

caprock mechanical stability refers to the ability of the caprock to resist external mechanical stresses, fluid pressures, and internal property changes during the underground storage of CO_2. The mechanical properties of the caprock itself and the stress state it is subjected to significantly influence its sealing performance. If the caprock fails, CO_2 may escape to the surface through faults or fractures [9].

Therefore, the evaluation of caprock mechanical stability involves multiple factors. Among them, the rock mechanical properties, as the fundamental physical characteristics of the caprock, directly determine its bearing capacity and deformation characteristics, which in turn have a significant impact on sequestration safety [10]. Geological structural features are also crucial, as they determine the overall stability of the sequestration area. In particular, structures such as faults and folds directly affect the risk of sliding or fracturing within the region [11]. Injection conditions directly influence the pressure and stress distribution in the caprock during the sequestration process, especially with variations in injection pressure and rate [12]. Additionally, geological stress plays a critical role in the long-term stability of the sequestration area. In deep sequestration, changes in geological stress can cause caprock failure or sliding, thereby compromising sequestration safety [13]. Finally, the characteristics of the caprock are essential to the sealing performance of the sequestration area, ensuring the long-term stability and safety of the stored gas.

2.2 Caprock Mechanical Stability Evaluation Model

Based on the actual conditions of CO_2 geological sequestration and the objectives of this study, the evaluation of caprock mechanical stability is divided into five main criteria: rock mechanical properties, geological structural features, injection conditions, geological stress, and caprock permeability characteristics. Each criterion includes multiple specific indicators, which serve as key factors for assessing caprock mechanical stability. Taking these factors into account, a caprock mechanical stability evaluation system is established (see Figure 1), with evaluation models built according to the target layer, criteria layer, and indicator layer. These indicators not only encompass the physical and mechanical properties of the caprock but also include external factors such as geological structural complexity, injection conditions, and geological stress.

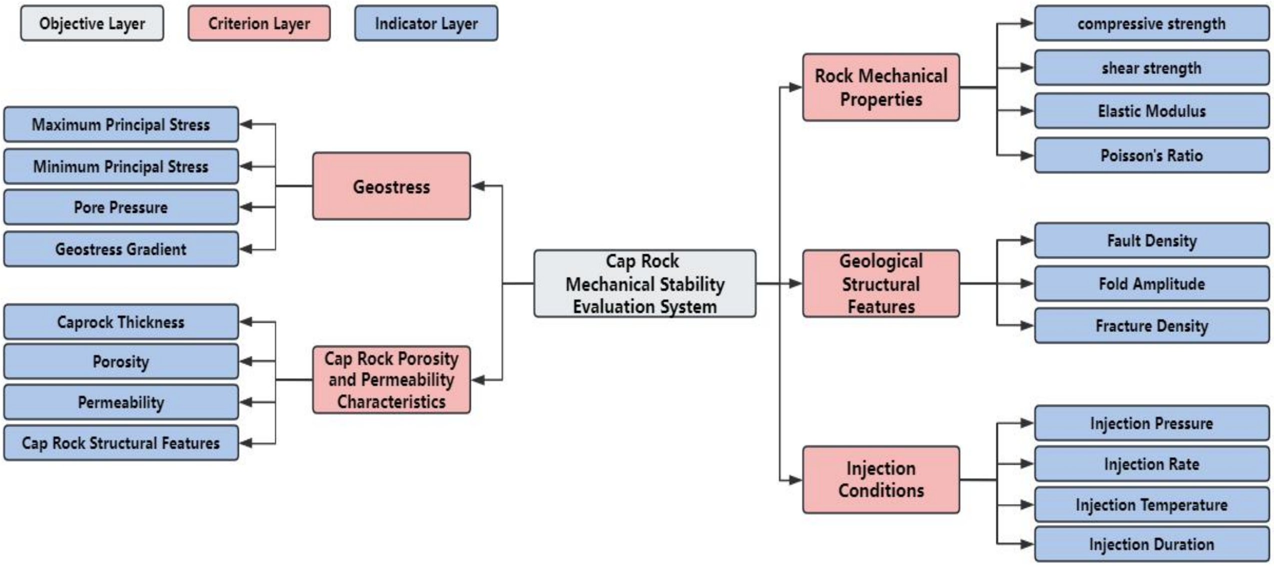

Figure 1: Caprock Mechanical Stability Evaluation System

2.3 Classification of the Importance of Criteria and Indicator Layers

In constructing the caprock mechanical stability evaluation system, the classification of the importance of the criteria and indicator layers is a critical step in the development of the evaluation framework. Based on the actual requirements of CO_2 geological sequestration and expert opinions, the Fuzzy Analytic Hierarchy Process (FAHP) is employed to determine the importance of each criterion and indicator layer, ensuring the scientific validity and rationality of the evaluation system.

First, the physical properties of the rock, including elastic modulus, compressive strength, and shear strength, govern the deformation and failure modes of the caprock under external stress [14]. These mechanical parameters directly affect the stability of the rock formation and are essential for evaluating the mechanical performance of the caprock during sequestration. Next, geological structural features such as faults and folds play a significant role in the evaluation of mechanical stability. Complex geological structures often result in stress concentration and the development of fractures, which may become pathways for CO_2 leakage. Therefore, it is crucial to closely monitor the impact of these structural features on the caprock's stability. Third, injection conditions are another important factor affecting caprock stability. The injection rate, pressure, and temperature of CO_2 alter the internal stress state of the caprock. In particular, under high-pressure injection conditions, localized stress concentration may cause deformation or even fracture. These injection and storage processes introduce various geomechanical issues, including induced seismicity and caprock failure. Additionally, geological stress, as a key factor in determining the stress distribution within the rock, directly influences the mechanical behavior of the caprock during sequestration. The magnitude and direction of geological stress control the deformation mode of the rock, which is crucial for ensuring sequestration safety. Finally, the porosity and permeability characteristics of the caprock are also of significant importance in evaluating the stability of the sequestration. caprocks with low permeability and high density help prevent CO₂ leakage, ensuring the long-term effectiveness of sequestration. By conducting a comprehensive weight analysis of factors such as rock physical properties, geological structural features, injection conditions, geological stress, and caprock porosity and permeability, this study establishes a multi-factor caprock mechanical stability evaluation system, as shown in Table 1, providing a theoretical basis for the safety assessment of CO₂ geological sequestration.

Table 1: Evaluation and Rating Standards for Cap Rock Mechanical Stability

indicator	concrete indicators	evaluation methods				
		Excellent(5)	Good(4)	Ordinary(3)	Below Average(2)	Poor(1)
Rock Mechanical Properties	Compressive Strength(MPa)	≥32	30-32	20-30	15-20	<15
	Shear Strength(MPa)	≥20	18-20	13-18	10-13	<10
	Elastic Modulus(GPa)	≥9.6	8.4-9.6	6-8.4	4.8-6	<4.8
	Poisson's Ratio	≤0.3	0.3-0.32	0.32-0.35	0.35-0.4	>0.4
Geological Structural Features	Fault Density (faults/km²)	≤0.1	0.1–0.3	0.3–0.5	0. 5–0.7	>0.7
	Fold Amplitude(m)	≤2	2–5	5–10	10–15	>15
	Fracture Density(fractures/m²)	≤1	1–3	3–5	5–7	>7
Injection Conditions	Injection Pressure(MPa)	8-18	18-20	20-22	22-24	>24
	Injection Rate (Mt/a)	≤1	1-1.2	1.2-1.4	1.4-1.6	>1.6
	Injection Temperature(°C)	35-45	45-50	50-55	55-60	>60
	Injection Duration (a)	≥25	15-25	12-15	10-12	<10
Geostress	Maximum Principal Stress(MPa)	≤20	20-25	25-28	28-30	>30
	Minimum Principal Stress(MPa)	≥12	10-12	8-10	6-8	<6
	Pore Pressure (MPa)	≤18	18-20	20-22	22-25	>25
	Geostress Gradient(kPa/m)	≤24	24-26	26-30	30-34	>34
Cap Rock Porosity and Permeability Characteristics	Caprock Thickness (m)	≥300	200-300	100-200	50-100	<50
	Porosity	Low	Relatively Low	Moderate	Relatively High	High
	Permeability	Low	Relatively Low	Moderate	Relatively High	High
	Cap Rock Structural Features	Dense with No Fractures	Dense with Microfractures	Low Fracture Density	Moderate Fracture Density	High Fracture Density

3. Establishment of the Weight Set

In the cap rock mechanical stability evaluation system, different criteria and indicators exert varying degrees of influence on the overall stability of the cap rock. To scientifically assess the importance of each indicator, it is necessary to assign weights to these indicators, thereby forming a weight set. By establishing the weight set, the evaluation system can not only comprehensively consider all factors but also highlight those with a greater impact, thereby enhancing the scientific accuracy and reliability of the evaluation results. Based on expert experience and relevant research findings, a first- and second-level fuzzy judgment matrix was constructed using the pairwise comparison method in the Analytic Hierarchy Process (AHP).

3.1 Method for Determining the Weight Vector

The main methods for determining weights include the maximum entropy method, square root method, specific vector method, and Analytic Hierarchy Process (AHP) [15, 16]. In this study, weights are determined through pairwise comparison of indicators and the construction of a judgment matrix. First, a fuzzy reciprocal judgment matrix FFF is constructed for indicators at the same level using the 0. 1–0. 9 scaling method, specifically:

$$F = \begin{matrix} f_{11} & f_{12} & \cdots & f_{1n} \\ f_{21} & f_{22} & \cdots & f_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ f_{n1} & f_{n2} & \cdots & f_{nn} \end{matrix} \qquad (1)$$

In the equation, f_{ij} represents the quantitative importance scale of factor i compared to factor j, determined using the 0. 1–0. 9 importance scale reference table (see Table 2). f_{ii}=0. 5, and f_{ij}=1-f_{ji}.

Table 2: 0.1~0.9 importance scale reference table

Scale	Importance level	Explanation
0.5	Equally important	When comparing the two elements, they are equally important.
0.6	Slightly important	When comparing the two elements, one element is slightly more important than the other.
0.7	Moderately important	When comparing the two elements, one element is moderately more important than the other.
0.8	Much more important	When comparing the two elements, one element is much more important than the other.
0.9	Extremely important	When comparing the two elements, one element is extremely more important than the other.
0.1, 0.2, 0.3, 0.4	Contrast comparison	If the comparison between element a_i and element a_j yields the judgment r_{ij}, then the judgment obtained by comparing element a_j with element a_i is $r_{ji}=1-r_{ij}$.

3.2 Determination of the Weight Vector for Primary Indicators

Listing the First-Level Fuzzy Reciprocal Judgment Matrices F_b for the Five Criteria Layers

$$F_b = \begin{pmatrix} 0.5 & 0.7 & 0.6 & 0.7 & 0.8 \\ 0.3 & 0.5 & 0.5 & 0.6 & 0.7 \\ 0.4 & 0.5 & 0.5 & 0.6 & 0.7 \\ 0.3 & 0.4 & 0.4 & 0.5 & 0.6 \\ 0.2 & 0.3 & 0.3 & 0.4 & 0.5 \end{pmatrix} \qquad (2)$$

Next, the weight vector W needs to be calculated.

$$W = (W_1, W_2, \cdots W_n)^T \qquad (3)$$

$$W_i = \frac{\sum_{j=1}^{n} f_{ij} + \frac{n}{2} - 1}{n(n-1)} \quad (i = 1,2\cdots,n) \qquad (4)$$

Here, $\sum_{j=1}^{n} f_{ij}$ represents the sum of the elements in the iii-th row. It follows that W_b= (0. 24, 0. 205, 0. 21, 0. 185, 0. 16) After determining the weight vector, the characteristic matrix W*can be determined using the weight vector, $W_{ij} = \frac{w_i}{w_i + w_j} (\forall i, j = 1,2,\cdots n)$, The resulting n-order matrix is the characteristic matrix of the fuzzy complementary judgment matrix F. To assess the rationality of the weight distribution, a consistency check is required. The compatibility index *I(F, W*)*is calculated by comparing the fuzzy complementary judgment matrix Fand its characteristic matrix W*. where

$$I(F,W^{*})=\frac{1}{n^{2}}\sum_{i=1}^{n}\sum_{j=1}^{n}\left|f_{ij}+w_{ji}-1\right| \qquad (5)$$

If $I(F, W^*)<\alpha$, the consistency check is considered passed, A smaller value of αindicates a higher requirement for consistency, with α=0. 1 typically used. Based on the above, the compatibility index for the first-level fuzzy matrix is I_b=0. 0837<0. 1, indicating that the consistency check is passed and the weight distribution is deemed reasonable.

3.3 Determination of the Weight Vector for Secondary Indicators

Based on the previous first-level indicators, and incorporating expert opinions, a corresponding judgment matrix is constructed to determine the weight vector for secondary indicators and perform consistency testing. The results are shown in Table 3.

Table 3: Weight Vector for Secondary Indicators and Consistency Test Results

Primary indicator	Secondary indicator weight vector	Consistency test result
Rock Mechanical Properties	W_{c1}=(0.3,0.267,0.233,0.2)	I_{c1}=0.0831<0.1
Geological Structural Features	W_{c2}=(0.417,0.317,0.267)	I_{c2}=0.0843<0.1
Injection Conditions	W_{c3}=(0.3,0.25,0.242,0.208)	I_{c3}=0.0899<0.1
Geostress	W_{c4}=(0.3,0.233,0.267,0.2)	I_{c4}=0.0831<0.1
Cap Rock Porosity and Permeability Characteristics	W_{c5}=(0.3,0.233,0.267,0.2)	I_{c5}=0.0831<0.1

4. Case Study Analysis

To evaluate the applicability of the proposed mechanical stability assessment system for cap rocks, this study applies the method to the Jilin Oilfield region. Located in the central and southern parts of the Songliao Basin, the Jilin Oilfield is one of China's major oil and gas reserves. The area surrounding the Daqingzi well is characterized by normal faults, with the overall geological structure trending mainly in the north-south direction, parallel to the axial line of the regional anticline. The stratigraphy in this region is relatively complete, with multiple layers of sedimentary rock formations, providing a favorable foundation for CO_2 geological sequestration.

The cap rock in the study area is primarily composed of dense mudstone, with low natural porosity and permeability, exhibiting excellent isolation properties. The mudstone layers are mainly found in the Nenjiang, Yaojia, and Qingshankou formations, with a cumulative thickness exceeding 200 meters, ensuring the long-term stability of CO_2 sequestration. For example, the mudstone layers in the Nenjiang, Sifangtai, and Mingshui formations, particularly the brown-red and brown-gray mudstones, have a relatively high fracture pressure, generally greater than 5 MPa. These layers also exhibit low diffusion coefficients and relative permeability, which effectively prevent the upward migration of CO_2. Additionally, the mineral composition of the cap rock mudstones includes a significant proportion of clay minerals and quartz, further enhancing resistance to fluid flow and maintaining their sealing capacity over extended periods.

This study investigates the mechanical parameters and geological characteristics of the cap rock in the Sifangtai Formation. The compressive strength of the mudstone in this area typically ranges from 30 to 35 MPa, while the shear strength is between 10 and 15 MPa. The elastic modulus is between 8.4 and 9.6 GPa, and the Poisson's ratio is approximately 0.25 to 0.3. The regional fault density is only about 0. 1 faults per km^2, indicating a low fracture frequency, which effectively reduces the risk of cap rock instability. Additionally, the fracture density in the mudstone cap rock is 1 to 3 fractures per m^2, which helps decrease the likelihood of CO_2 migration along fractures.

To ensure the integrity of the cap rock during CO_2 injection, the injection pressure is typically controlled between 18 and 20 MPa, with an injection rate set at 1 to 2 Mt/year. The injection temperature is maintained between 45 and 50°C to minimize the potential thermal stress on the cap rock and keep CO_2 in a supercritical state. The injection process is generally planned to last over 20 years. The region's maximum principal stress is between 25 and 30 MPa, while the minimum principal stress is close to 12 to 15 MPa, creating a favorable geological stress environment. The mudstone cap rock has low porosity and a permeability of less than 10^{-4} mD, which effectively inhibits gas leakage. Furthermore, the cap rock thickness exceeds 200 meters, providing a robust pressure barrier for the sequestration process. These combined characteristics indicate that the cap rock possesses high storage safety.

Based on the macro parameters and field conditions of the region, the secondary indicators are scored and quantified in accordance with the cap rock mechanical stability classification standards, as shown in Table 4.

Table 4: Cap rock mechanical stability classification standards

indicator	weight	concrete indicators	indicator value	Evaluation score	Item weight	Weighted score	Final score
Rock Mechanical Properties	0.24	Compressive Strength(MPa)	33	5	0.3	1.50	1.02
		Shear Strength(MPa)	13	3	0.2667	0.80	
		Elastic Modulus(GPa)	9	4	0.2333	0.93	
		Poisson's Ratio	0.3	5	0.2	1.00	
Geological Structural Features	0.205	Fault Density (faults/km²)	0.1	5	0.4167	2.08	0.91
		Fold Amplitude(m)	3	4	0.3167	1.27	
		Fracture Density(fractures/m²)	2	4	0.2667	1.07	
Injection Conditions	0.21	Injection Pressure(MPa)	20	4	0.3	1.20	0.68
		Injection Rate (Mt/a)	2	1	0.25	0.25	
		Injection Temperature(°C)	48	4	0.2417	0.97	
		Injection Duration (a)	20	4	0.2083	0.83	

Geostress	0.185	Maximum Principal Stress(MPa)	29	2	0.3	0.60	0.59
		Minimum Principal Stress(MPa)	14	5	0.2333	1.17	
		Pore Pressure (MPa)	21	3	0.2667	0.80	
		Geostress Gradient(kPa/m)	27	3	0.2	0.60	
Cap Rock Porosity and Permeability Characteristics	0.16	Caprock Thickness (m)	200	4	0.3	1.20	0.61
		Porosity	Relatively Low	4	0.2667	1.07	
		Permeability	Relatively Low	4	0.2333	0.93	
		Cap Rock Structural Features	Low Fracture Density	3	0.2	0.60	

Based on the evaluation of the factors influencing cap rock stability at the site, the overall stability score for the cap rock is 3. 81 out of a maximum of 5. This indicates a favorable cap rock stability, and the selected site is suitable for CO_2 geological sequestration.

5. Conclusion

(1) This study, based on the Analytic Hierarchy Process (AHP) and incorporating fuzzy mathematics, develops a comprehensive evaluation system for assessing the mechanical stability of cap rocks following CO_2 injection into saline aquifers.

(2) Through engineering case studies, the FAHP model effectively evaluates the mechanical stability of cap rocks. The results meet the storage safety requirements, demonstrating the model's practicality and accuracy.

(3) The model quantitatively assesses the impact of various uncertainties on the outcome, providing valuable technical support for long-term storage safety evaluations and enhancing the scientific rigor and reliability of decision-making. It also offers a basis for evaluating CO_2 storage projects in similar regions.

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