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Research Article

Study and Application of Safety Risk Evaluation Model for CO_2 Geological Storage Based on Uncertainty Measure Theory

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Analyzing showed that the safety risk evaluation for CO_2 geological storage had important significance. Aimed at the characteristics of CO_2 geological storage safety risk evaluation, drawing on previous research results, rank and order models for safety risk evaluation of CO_2 geological storage were put forward based on information entropy and uncertainty measure theory. In this model, the uncertainty problems in safety risk evaluation of CO_2 geological storage were solved by qualitative analysis and quantitative analysis, respectively; uncertainty measurement functions for the relevant factors were established based on experimental data; information entropy theory was applied to calculate the index weight of factors; safety risk level was judged based on credible degree recognition criterion and ordered. This model was applied in three typical zones of Erdos and Hetao basins. The results show that uncertainty measure method is objective and reasonable and can be used as a new way to evaluate the safety of CO_2 geological storage sites in the future.

1. Introduction

The extensive use of coal, oil, natural gas, and other fossil fuels significantly increases the CO_2 content of the atmosphere. This leads to global warming and poses a serious threat to humans and the sustainable development of our society and economy. CO_2 emissions have become a major problem. At present, scientists agree that CO_2 capture and storage is an important and effective strategy for easing climate change. It can also be effectively, comprehensively, and sustainably applied to resource development, energy utilization, economic growth, and ecological environment protection, among others [1, 2].

A geological implementation of CO_2 storage could safely trap CO_2 in rock cracks in the deep crust of the earth, but this takes a long time. Furthermore, temperatures and pressure changes inside the earth cause sudden geological events such as volcanoes and earthquakes, which trigger tectonic movements. Additionally, human engineering activities such as abandoned wells could lead to CO_2 leaks [3]. Thus, CO_2 geological sequestration technology is a "double-edged sword"; it could effectively alleviate the environmental disaster of climate change, but, at the same time, it could induce geological environmental disasters. It is therefore imperative that the people research methods for geologically storing CO_2 and evaluate the security risks.

Recently, there have been several investigations into evaluating the risks of CO_2 geological storage, and researchers have proposed many risk evaluation methods. However, the proposed standards and methods have mainly been aimed at the storage medium and lack of systemic evaluation weight methods [4–6]. CO_2 geological storage security risk is a comprehensive combination of many internal and external factors, which are random, fuzzy, grey, and uncertain. It is important that the people analyse the uncertainties of this information. In this regard, uncertainty mathematical theory provides a better way. Based on previous CO_2 geological storage security risk evaluation research and referring to the mathematical theory of uncertainty [7, 8], a new method is proposed for evaluating the risks in this paper.

2. Uncertainty Measure

Let $x_1, x_2, \ldots, x_n$ be n objects in the index space $X = \{x_1, x_2, \ldots, x_n\}$. Each object has m single evaluation index spaces; that is, $I = \{I_1, I_2, \ldots, I_n\}$. x_i can be expressed as a m-dimensional vector $x_i = \{x_{i1}, x_{i2}, \ldots, x_{im}\}$. x_i has p evaluation levels, and its evaluation level space is $U = \{C_1, C_2, \ldots, C_p\}$, where C_k indicates the kth level. The kth level is stronger than the $(k+1)$th level; that is, $C_k > C_{k+1}$. Then, $\{C_1, C_2, \ldots, C_p\}$ is an ordered partition class in evaluation space U.

2.1. Uncertainty Measure for a Single Index. Let $\mu_{ijk} = \mu(x_{ij} \in C_k)$ indicate that measured value x_{ij} belongs to C_k (the kth evaluation level). μ must satisfy

$$0 \le \mu\left(x_{ij} \in C_k\right) \le 1$$
$$\left(i = 1, 2, \ldots, n;\ j = 1, 2, \ldots, m;\ k = 1, 2, \ldots, p\right), \quad (1)$$

$$\mu\left(x_{ij} \in U\right) = 1$$
$$\left(i = 1, 2, \ldots, n;\ j = 1, 2, \ldots, m\right), \quad (2)$$

$$\mu\left(x_{ij} \in \bigcup_{l=1}^{k} C_l\right) = \sum_{l=1}^{k} \mu\left(x_i \in C_l\right) \quad (k = 1, 2, \ldots, p). \quad (3)$$

Equation (2) means μ meets the "normalization" for evaluation space U; equation (3) means μ meets the "additivity" for evaluation space U. Because it satisfies (1), (2), and (3), μ is called the uncertainty measure or measure [9–11].

The matrix

$$\left(\mu_{ijk}\right)_{m\times p} = \begin{bmatrix} \mu_{i11} & \mu_{i12} & \cdots & \mu_{i1p} \\ \mu_{i21} & \mu_{i22} & \cdots & \mu_{i2p} \\ \vdots & \vdots & \vdots & \vdots \\ \mu_{im1} & \mu_{im2} & \cdots & \mu_{imp} \end{bmatrix} \quad (4)$$

is the single index evaluation matrix. When constructing it, the single index measure function must be first established. Existing methods for constructing this function include linear, exponential, parabola, and sinusoidal functions. Regardless of its type, the simulation function must be nonnegative, unitary, and additive. Suitable uncertainty measures can be selected according to the characteristics of specific indexes. A linear uncertainty measure is currently the most popular and simple, so it was used in this paper.

2.2. Determining the Index Weight. Let w_{ij} $(0 \le w_{ij} \le 1,\ \sum_{j=1}^{m} w_{ij} = 1)$ represent the importance of I_j relative to the other indexes, and let w_{ij} be the weight of I_j $(j = 1, 2, \ldots, m)$. The weight of each index is determined using information entropy theory [12–15]. That is,

$$v_{ij} = 1 + \frac{1}{\lg p} \sum_{i=1}^{p} \mu_{ijk} \lg \mu_{ijk},$$
$$w_j = \frac{v_{ij}}{\sum_{i=1}^{n} v_{ij}}. \quad (5)$$

2.3. Comprehensive Measure for Multiple Indexes. Using the index weights, the multi-index comprehensive measure can be calculated to evaluate $\mu_{ik} = \sum_{j=1}^{m} w_{ij}\mu_{ijk}$ $(i = 1, 2, \ldots, n;\ j = 1, 2, \ldots, m;\ k = 1, 2, \ldots, p)$. Here, if $0 \le \mu_k \le 1$, $\sum_{k=1}^{p} \mu_{ik} = 1$, then μ_{ik} is known as the uncertainty measure, and $\{\mu_{i1}, \mu_{i2}, \ldots, \mu_{ip}\}$ is the multi-index comprehensive evaluation measure vector of x_i.

2.4. Recognition Criterion of the Credibility. If $C_1 > C_2 > \cdots > C_p$, a credibility criterion can be introduced. Let λ be the degree of credibility, where $\lambda \ge 0.5$; typically use $\lambda = 0.6$ or 0.7. If $k_0 = \min(k : \sum_{l=1}^{k_p} \mu_{il} \ge \lambda,\ 1 \le l \le k)$, then it is considered to belong to C_{k_0}.

2.5. Ordering. As well as discriminating x_i's evaluation level, sometimes it must be ordered according to its importance. If $C_1 > C_2 > \cdots > C_p$, the command value of C_{l_0} is n_{l_0}. Then, $n_{l_0} > n_{l+1}$, and $q_{x_i} = \sum_{l=1}^{p} n_l \mu_{il}$, where q_{x_i} is the uncertainty importance degree of evaluation factor x_i. $q = \{q_{x_1}, q_{x_2}, \ldots, q_{x_p}\}$ is called the uncertainty importance vector. x_i is ordered according to the value of q_{x_i}.

3. Example Application

The data of 3 typical zones in the Erdos and Hetao basins provided by Wang [16] were taken as the research object. Drawing from the results in [17–20], we set the cover layer lithology, total thickness of the cover layer, seismic safety, presence of drilling and abandoned wells within 25 km^2 of the site, topography, main wind directions between the CO_2 perfusion site and residents, distance from permanent residents, and distance from surface drinking water sources such as rivers and reservoirs, as evaluation factors. The qualitative parameters such as the cover layer lithology, seismic safety, presence of drilling and abandoned wells within 25 km^2 of the site, topography, and main wind directions between the CO_2 perfusion site and residents are valued by a semiquantitative method. The grading standards and values are shown in Table 1. The values of the quantitative parameters such as total thickness of the cover layer, distance from permanent residents, and distance from surface drinking water sources such as rivers and reservoirs were valuable measures, as shown in Table 2. Each evaluation index was classified and valued, and the evaluation set is $\{C_1, C_2, C_3\}$ (or high, medium, and low). The basic situations of number 1, number 2, and number 3 target zones are shown in Table 3.

Table 1: Classification criteria of the qualitative indexes.

Grade	Value	Factors				
		The cover layer lithology	Seismic safety	Presence of drilling and abandoned wells within 25 km^2 of the site	Topography	Main wind directions between the CO_2 perfusion site and residents
High	3	Shale and compact limestone	Low	Many and not sealed	Lying and complex terrain	Upwind
Medium	2	Mud rocks	Medium	Exist and have been sealed	Broad and shallow terrain	Side wind
Low	1	Evaporating rocks	High	No	High convex open terrain	Downwind

Table 2: Classification criteria of quantitative indexes.

Grade	Factors		
	Total thickness of the cover layer (m)	Distance from permanent residents (m)	Distance from surface drinking water sources such as rivers and reservoirs (m)
High	<40	<800	<150
Medium	40–80	800±	150±
Low	>80	>800	>150

3.1. Single Index Measure Function. According to the constructing method of single index measure function, combined with grading standards in Tables 1 and 2, and the specific values in Table 3, single index measure functions are constructed in order to obtain the measured value of each evaluation index. The single index measure functions of qualitative indexes such as the cover layer lithology, seismic safety, presence of drilling and abandoned wells within 25 km^2 range of the site, topography, and main wind direction between the CO_2 perfusion site and residents are shown in Figure 1. The single index measure functions of quantitative indexes such as total thickness of the cover layer are shown in Figure 2. We used the same method for constructing the single index measure function for distance from permanent residents and distance from surface drinking water sources such as rivers and reservoirs.

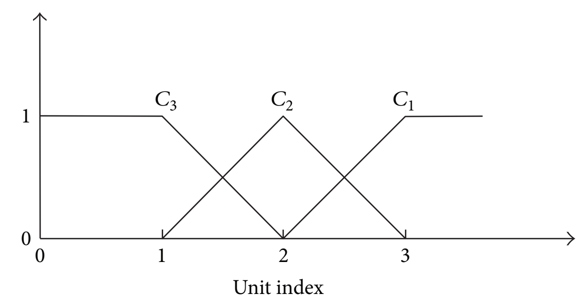

Figure 1: Single index measure function for the cover layer lithology, seismic safety, presence of drilling and abandoned wells within 25 km^2 range of the site, topography, and main wind direction between the CO_2 perfusion site and residents.

According to single index measure function mentioned above and combined with the actual data in Table 3, the single index evaluation matrix of 3 target zones can be calculated. For example, the single index evaluation matrix for number 1 target zone was

$$\mu_{A_1} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 1 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix}. \quad (6)$$

3.2. Calculating the Multiple Index Measures Evaluation Matrix. Formula (5) determines the weight of each index. The weights of the evaluation indexes for number 1 target zone were $\{w_1, w_2, w_3, w_4, w_5, \ldots, w_8\} = \{0.125, 0.125, 0.125, 0.125, 0.125, 0.125, 0.125, 0.125\}$. Using the single index measure matrix and the multiple index calculation formula, the multiple index vector was $\mu_1 = \varpi_1 \cdot \mu_{A_1} = \{0.125, 0.5, 0.375\}$.

3.3. Degree of Credibility. We set the degree of credibility to $\lambda = 0.6$ and used the multiple index comprehensive evaluation measure vector and credibility formula to calculate that $k_0 = 0.625 > 0.5$. Then, the grade of number 1 target zone was "medium." The other two target zones are evaluated in a similar way. The results are shown in Table 4. Our evaluations of the safety risk grade of each target zone match well with the results obtained by Wang [16] using fuzzy comprehensive evaluation method.

3.4. Ordering of the Safety Risk Grades. According to order formula, because $C_1 > C_2 > C_3$, we can take $n_l = 8 - 2q$,

Table 3: Survey statistics for the evaluation index.

Research zone	The cover layer lithology	Total thickness of the cover layer (m)	Seismic safety	Presence of drilling and abandoned wells within 25 km^2 of the site	Topography	Main wind directions between the CO_2 perfusion site and residents	Distance from permanent residents (m)	Distance from surface drinking water sources such as rivers and reservoirs (m)
Number 1 target zone	Mud rock	40–80	Medium	No	Complex terrain	Downwind	>800	150±
Number 2 target zone	Mud rock	40–80	High	No	High convex open terrain	Side wind	800±	>150
Number 3 target zone	Mud rock	40–80	Low	No	Broad and shallow terrain	Downwind	>800	<150

Table 4: Evaluation results comparing the uncertainty measure models and the fuzzy comprehensive evaluation results from Wang [16].

Research zone	General uncertainty measure			Evaluation results of uncertainty measure model	Evaluation results of fuzzy comprehensive evaluation
	C_1	C_2	C_3		
Number 1	0.125	0.5	0.375	II	II
Number 2	0	0.5	0.5	III	III
Number 3	0.25	0.375	0.375	II	II

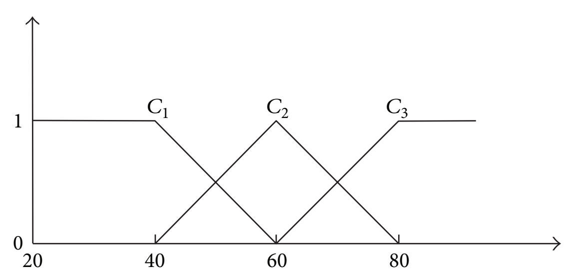

Figure 2: Single index measure function for total thickness of the cover layer.

where $1 \le q \le 3$, so that $q = [q_1 \ \ q_2 \ \ q_3] = \{3.5, 3, 3.75\}$. Ordering the CO_2 geological storage safety risk grade of 3 target zones, we see that the risk is highest in number 3 target zone, followed by number 1 target zone and then number 2 target zone.

4. Conclusions

(1) According to the random, fuzzy, grey, and uncertainty characteristics of CO_2 geological storage safety risk evaluation, an evaluation method of CO_2 geological storage safety risk based on uncertainty measure theory was put forward, and the evaluation model of CO_2 geological storage safety risk was established based on uncertainty measure theory.

(2) The index weights were objectively calculated based on information entropy theory. The safety risk of CO_2 geological storage was evaluated using credibility measurements, and the risk grades were ranked. This method is objective and reasonable and provides a new way to evaluate the safety risk of CO_2 geological storage.

(3) The method was applied to data from 3 typical zones in Erdos and Hetao basins. The results matched well with those obtained by the fuzzy comprehensive evaluation method in Wang [16].

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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