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An investigation of key parameters involved in fault activation mechanisms in CO_2 storage

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ABSTRACT

The objective of this research work is to conduct a comprehensive study of fault activation mechanisms and delve into the mechanisms involved in fault reactivation processes in CO_2 storage. Faults constitute a major component of geological formations and change the rock mass system's mechanical behavior significantly, in particular at large scales. The focus of this research is to conduct an analysis of key caprock geomechanical design parameters and compare the significance of each parameter. In this study, the well-documented studies on caprock integrity analysis and fault activation were reviewed and evaluated. The key geomechanical design parameters associated with CO_2 storage were identified and discussed. Accordingly, a procedure for weighting these parameters was developed based on the Fuzzy Analytic Hierarchy Process (FAHP) and used in the comparison of the selected parameters. Based on the developed weighting scheme, the fault friction angle has the highest significance in caprock behavior followed by rock mass permeability and regional in-situ stress ratio. The obtained results are in harmony with practical observations and published research works. With further verification, the proposed approach can be used in the selection of key geomechanical design data required for CO_2 storage site analysis and design.

KEYWORDS

CO_2 Storage, Fault activation mechanisms, Numerical modelling, weighting procedures

1. INTRODUCTION

To safely store Carbone dioxide, it is vital to ensure the integrity of the caprock during the CO_2 injection process and production within a reservoir. A change in fluid pressure and temperature within a geological reservoir/formation affects the regional in-situ stress within the reservoir and surrounding rock. Accordingly, the potential hazards associated with CO_2 storage are a reactivation of major pre-existing discontinuities and faults and the creation of new fractures within the caprock zone, which may breach the hydraulic integrity of the storage site. Faults constitute a major component of storage site caprock and change the rock mass system's mechanical behavior significantly, in particular at large scales. The hydraulic integrity of the reservoir rock mass will be assessed by investigating potentials for shear fracturing, tensile fracturing, and fault and pre-existing discontinuity reactivation. Faults and major discontinuities exist in almost all rock masses. In particular, when we deal with rock mass at large scales as we face in CO_2 storage, faults play a significant role in the deformational behavior of the rock mass and dominate the overall behavior of the rock system. Characterization and determination of fault's strength properties have always been a challenge in rock engineering. From a mechanical stress field point of view faults themselves, affect the in-situ stress regime significantly locally and change the stress field differently depending on the faulting mechanism, shear zone thickness, dip, dip direction, strike length, and depth.

An accurate representation of fault geometry and characterization of fault behavior and fault properties is a major component of geomechanics modeling of CO_2 storage projects.

2. GEOMECHANICAL INVESTIGATIONS OF FAULT ACTIVATION MECHNISMS

Rutqvist et al. (2013) presented a review of modeling studies on fault reactivations and induced seismicity during underground CO_2 injection. The modeling exercises were of coupled mechanical-fluid flow type and included quantitate analysis of fault weakening and rupture as well as seismic activities. These model simulations showed that the critical factors affecting seismicity due to CO_2 injection are the local in situ stress field, fault orientation and size, fault strength, and injection pressure. They numerically simulated the activation potential of a 1km long fault and showed that the magnitude of produced seismic event would likely be less than about 3.6, even if the entire 1 km fault would be activated. The study demonstrated that fault reactivation, even associated with relatively small seismic or aseismic events, could potentially increase CO_2 seepage out of the intended storage complex and therefore reduce the effectiveness of a CO_2 storage operation.
Urpi et al. (2016) conducted a dynamic analysis of CO_2-injection-induced fault rupture with slip-rate dependent friction coefficient. An idealized CO_2 injection scenario was simulated employing the FLAC-3D code coupled with the TOUGH2 code. The mechanical stress field was coupled to multiphase fluid flow to evaluate the stress and pressure perturbations induced by fluid injection and the response of a nearby normal fault. The FLAC-3D interface element was used to simulate the frictional behavior of the fault in a coupled hydro-mechanical manner, capable of computing the poro-elastic stresses acting on the fault plane and the pressure field perturbed by the fluid injection. Different scenarios of injection rate and fault rheologies were simulated to demonstrate the deformation process on fault. The study showed that rupture on the fault plane occurs at the bottom of the reservoir which is in harmony with analytical solutions. These results show that the magnitude values are heavily influenced by the initial drop in friction angle and it takes only 1 µm of fault slip until the rate-dependency kicks in. Therefore, an initial shear strength drop is necessary to nucleate dynamic shear slip on the fault. It was concluded that a different injected fluid can perturb the pressure and stress distribution differently. This study showed that the considered fault rheology can significantly affect the modeling results.
Jeanne et al. (2017) investigated the effects of the distribution and evolution of the coefficient of friction along a fault and the seismic activity associated with a hypothetical CO_2 sequestration operation. They postulated that the pressure buildup inside the storage formation can induce slip along pre-existing faults and create seismic events felt by the population. The role of variations in friction coefficient and friction law on fault stability was evaluated. A hypothetical industrial-scale carbon sequestration project in the Southern San Joaquin Basin, USA was simulated numerically. They concluded that the variation in fault friction coefficient has a significant effect on seismic activity ranging from 1.88 to 5.88 in event magnitude. Moreover, the fault friction coefficient causes stress build-up on the fault surface before rupture, and the presence of an argillaceous caprock can prevent the development of large-magnitude seismic events.
Zappone et al. (2020) discussed the results of an experiment on the injection and storage of carbon dioxide (CO_2), the purpose of which was to study the integrity of sealing faults and caprock. The experiment was conducted in a deep saline aquifer of the Northern Carnic Alps in Italy and was analyzed in Mont-Terri underground laboratory. Due to the fact that the Opalinus clay formation is one of the good analogs of the rock for storing CO2 at depth, CO_2-saturated salt water was pumped into the upper part of a 3-meter fault in this clay. It was found that CO2 did not migrate through the sealing defects, indicating that the defects effectively sealed the CO_2 in the injection zone. However, the injection of CO_2 affected the integrity and permeability of the caprock with the formation of new cracks. The conducted experiments show that sealing faults can be effective in preventing CO_2 migration in deep saline aquifers. Overall, the study provides valuable information about the challenges associated with the safe storage of CO_2 in deep saline aquifers.
Guglielmi et al. (2021) conducted field-scale fault reactivation experiments by fluid injection. The effect of liquid injection on the reactivation of faults in caprock, which acts as a sealing layer of rock preventing the leakage of liquids like natural gas and carbon dioxide (CO_2), was investigated. The focus of this study was CO_2 absorption in geological formations. It was found that liquid injection can cause fault reactivation but the leakage due to this is not significant. Also, the results of the study suggest that the reactivation of the fault may be aseismic, that is, it cannot cause seismic activity. They concluded that aseismic movement that dominates fault activation suggests that measurements of seismicity can hardly be used to track loss of caprock integrity.

3. KEY GEOMECHANICAL PARAMETERS AFFECTING FAULT ACTIVATION

Storage of CO_2 in geological information is associated with high risks. It is well established that the investigation of geomechanical parameters at the design stage of CO_2 storage sites provides the reservoir rock mass characteristics, which are associated with some risks in the design. The inherent uncertainties that exist in geomechanical data pose significant risks in the geomechanical design of CO_2 storage sites. From a realistic design and risk assessment point of view, it is essential to determine a suitable weighting strategy for risk-prone design parameters. The goal of this research is to develop a realistic weighting procedure to assess and compare various geomechanical parameters that are important in the design of CO_2 storage sites.
In this study, seven key geomechanical parameters used in the geomechanical analysis of CO_2 storage sites were selected, and a weighting procedure was developed using the Fuzzy Analytic Hierarchy Process (FAHP) method. The developed weighting methodology is presented in detail in Mortazavi and Kuzembayev (2022) and was employed here to demonstrate the significance of various parameters associated with CO_2 storage. The selected parameters were chosen based on a thorough literature review of geomechanical analyses conducted on CO_2 storage sites (Rutqvista et al., 2013; White et al., 2014; Urpi et al., 2016; Jeanne et al., 2017; Zappone et al., 2020; Guglielmi et al., 2021). The obtained preliminary results show that FAHP is a reliable method for weighting geomechanical parameters and can be used as a guide in the selection of key design parameters associated with CO_2 storage in geological information. An overview of the employed methodology is presented in the next sections.

3.1. FAHP-based weighting procedure

The Fuzzy Analytical Hierarchy Process (FAHP) method proposed by Buckley (1985) forms the basis of the proposed weighting methodology. The Fuzzy Analytical Hierarchy Process (FAHP) is a multi-criteria decision-making (MCDM) method based on the hierarchical structure analysis and systematic determination of the criteria weights using the fuzzy set theory. The criteria weight depends on linguistic evaluation provided by experts according to their experience and knowledge. A weighting process based on fuzzy logic is a more appropriate approach to overcome uncertainties; in some cases, decision-makers are more confident in giving a judgment range than fixed values. FAHP is used in a wide range of fields, such as risk assessment, energy, business, engineering, and others (Mardani et al., 2015). Considering the significant uncertainties faced in geological and geomechanical information, it is critical to have a weighting procedure to determine the significance of various parameters and assign the available budget in a more realistic way to determine the data required for the final design. It should be realized that there are a variety of methods developed based on the FAHP method. In this study, the geometric mean method using the triangular membership function was used. The geometric mean method was first developed by Buckley (1985) to extend the AHP to the situation of using linguistic variables. In this method, a unique fuzzy number is determined for the weight of the selected parameters, and the method is managed more easily mathematically. Moreover, the method is more suitable for cases in which there is a lack of sufficient data and a high scatter in the available data. The theoretical basis of the method is outlined in Buckley (1985) and further elaborated in Mortazavi and Kuzembayev (2022).

3.2. Selection of key geomechanical parameters involved in CO_2 storage

The Caprock geomechanical parameters are key components of underground CO_2 storage site design that affect the safety and success of the storage operation significantly. Complexities associated with in-situ rock properties at large scale, the existence of major geological structures such as faults, the coupling of hydro-mechanical stress fields involved, and complicated boundary conditions associated with CO_2 storage sites make this process very complicated, and conventional design methods may lead to significant errors. Moreover, the accuracy of design data plays a key role in the success of the design process. Accordingly, a specific group of physical and mechanical characteristics is measured in the laboratory or by in situ testing to determine the Caprock design parameters.
A set of key host rock mass physical, mechanical, in-situ, and strength parameters was selected for the analysis presented here. These parameters were selected based on the top literature published on CO_2 storage geomechanical design outlined in section 3. Accordingly, the following geomechanical parameters that are used in caprock integrity analysis of CO_2 storage sites, were selected for the evaluation and application of the proposed weighting procedure.

Table 1. Key geomechanical parameters involved in caprock integrity analysis

Parameter	Definition
P1	Fault friction angle
P2	Rock mass deformation modulus
P3	Rock mass permeability
P4	In-situ horizontal to vertical stress ratio (S_h/S_v)
P5	Fault cohesion
P6	Rock mass porosity
P7	Rock mass density

3.3. Weighting of the selected parameters involved in CO_2 storage

In the FAHP methods, fuzzy pairwise comparison matrices were constructed by using linguistic evaluations with respect to the decision-makers' judgments. The typical linguistic variables for pairwise comparison of each criterion are shown in Table 2.

Table 2. Linguistic Variables for Pairwise Comparison of Each Criterion

Linguistic Variables	Triangular Fuzzy Scale	Triangular Fuzzy Reciprocal Scale
Equally strong	(1, 1, 1)	(1, 1, 1)
Moderately strong	(2, 3, 4)	(1/4, 1/3, 1/2)
Strong	(4, 5, 6)	(1/6, 1/5, 1/4)
Very string	(6, 7, 8)	(1/8, 1/7, 1/6)
Extremely strong	(9, 9, 9)	(1/9, 1/9, 1/9)
	(1, 2, 3)	(1/3, 1/2, 1)
	(3, 4, 5)	(1/5, 1/4, 1/3)
Intermediate values	(5, 6, 7)	(1/7, 1/6, 1/5)
	(7, 8, 9)	(1/9, 1/8, 1/7)

In the proposed method by Buckley (1985), in step one a fuzzy pairwise comparison matrix, $\widetilde{D} = [\widetilde{a}_{ij}]$, is constructed based on the significance of selected parameters. Then, the fuzzy geometric mean value, $\tilde{r}_i$, is computed for each parameter *i* as;

$$\tilde{r}_i = (\tilde{a}_{i1} \times \tilde{a}_{i2} \times ... \times \tilde{a}_{in})^{1/n} \qquad (1)$$

The fuzzy weight $\widetilde{w}_i$ for each parameter *i* is calculated as;

$$\widetilde{w}_i = \tilde{r}_i \times (\tilde{r}_1 + \tilde{r}_2 + \cdots + \tilde{r}_n)^{-1} \quad (2)$$

where $\tilde{r}_k = (l_k, m_k, u_k)$ and $(\tilde{r}_k)^{-1} = \left(\frac{1}{u_k}, \frac{1}{m_k}, \frac{1}{l_k}\right)$

In the last step, the fuzzy weights are defuzzified by any difuzzification method. In this study, the Center of Area (CoA) method was used. Implementing the above procedure the weighting of the selected parameters was determined. The obtained results are presented in Tables 3 to 6.

Table 3. The pairwise comparison matrix

Parameters	P1	P2	P3	P4	P5	P6	P7
P1	1	4	2	3	4	5	7
P2	0.25	1	0.20	0.25	4	5	5
P3	0.50	5	1	3	5	6	6
P4	0.33	4	0.33	1	4	5	5
P5	0.25	0.25	0.20	0.25	1	2	3
P6	0.20	0.20	0.17	0.20	0.5	1	2
P7	0.14	0.20	0.17	0.20	0.33	0.50	1
Sum	2.68	14.65	4.07	7.90	18.83	24.50	29.00

Table 4. The calculated pairwise comparison matrix for geomechanical parameters involved in CO_2 storage

P's	P1			P2			P3			P4			P5			P6			P7		
P1	1	1	1	3	4	5	1	2	3	2	3	4	3	4	5	4	5	6	6	7	8
P2	0.20	0.25	0.33	1	1	1	0.20	0.25	0.33	0.20	0.25	0.33	0.20	0.25	0.33	0.20	0.25	0.33	0.20	0.25	0.33
P3	0.33	0.50	1	0.33	0.5	1	1	1	1	0.33	0.50	1.00	0.33	0.50	1.00	0.33	0.50	1.00	0.33	0.50	1.00
P4	0.25	0.33	0.50	0.25	0.33	0.50	0.25	0.33	0.50	1	1	1	0.25	0.33	0.50	0.25	0.33	0.50	0.25	0.33	0.50
P5	0.20	0.25	0.33	0.20	0.25	0.33	0.20	0.25	0.33	0.20	0.25	0.33	1	1	1	0.20	0.25	0.33	0.20	0.25	0.33
P6	0.17	0.20	0.25	0.17	0.20	0.25	0.17	0.20	0.25	0.17	0.20	0.25	0.17	0.20	0.25	1	1	1	0.17	0.20	0.25
P7	0.13	0.14	0.17	0.13	0.14	0.17	0.13	0.14	0.17	0.13	0.14	0.17	0.13	0.14	0.17	0.13	0.14	0.17	1	1	1

Based on the criteria given by Buckley (1985), the determined fuzzy pairwise comparison is consistent. Accordingly, the calculated geometric mean $\tilde{r}_i$ values and fuzzy weights $\widetilde{w}_i$ are calculated and presented in Table 5.

Table 5. The defuzzified and normalized weights determined for key parameters associated with CO_2 storage

Parameters	$\widetilde{w}_i$			$\widetilde{w}_{ave}$	Norm	Weight (%)
P1	0.35	0.62	0.99	0.65	0.59	59.41
P2	0.04	0.06	0.10	0.06	0.06	5.90
P3	0.06	0.11	0.25	0.14	0.13	12.64
P4	0.04	0.08	0.14	0.09	0.08	7.88
P5	0.04	0.06	0.10	0.06	0.06	5.90
P6	0.03	0.05	0.08	0.05	0.05	4.77
P7	0.02	0.04	0.05	0.04	0.04	3.51
Sum				1.10	1.0	100

The final sorted weights determined for the key geomechanical parameters used as an input in the design of underground CO_2 storage sites are summarized in Table 6.

Table 6. The final sorted weights determined for key parameters associated with CO_2 storage

Parameters	Weight (%)
Faults friction angle (P1)	59.41
Rock mass permeability (P3)	12.64
In-situ stress ratio (S_h/S_v) (P4)	7.88
Rock deformation modulus (P2)	5.90
Fault cohesion (P5)	5.90
Rock mass porosity (P6)	4.77
Rock mass density (P7)	3.51

4. CONCLUSIONS

With regard to the data-limited nature of the geomechanics design problem and the uncertainties associated with design data, it is vital to have a methodology to distinguish the significance of design parameters. In this study, the application of FAHP to the evaluation of key geomechanical design data of CO_2 storage sites was demonstrated and a weighting scheme was developed. Among the seven parameters that play role in the overall caprock, which has fault structures, the fault friction angle has the highest significance followed by rock mass permeability and in-situ stress ratio. The predicted weightings were determined based on expert opinions compiled from the top scientific papers published in highly ranked journals. The obtained results may be subjective to the expert opinions but are in harmony with mechanistic analyses conducted on geomechanical design aspects of CO_2 storage. If a more comprehensive survey of expert opinion is carried out at an international level and used as an input to the developed weighting procedure, then the obtained results would be more reliable and can be used as an aid in the design of new CO_2 storage sites. A comprehensive questionnaire of key geomechanical parameters involved in CO2 storage is under preparation. It is intended to send this questionnaire to at least 100 top international experts involved in CO2 storage. This is work in progress and will provide valuable data for the study.

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