# PROBABILISTIC ANALYSIS OF DRAUPNE SHALE CAPROCK RELIABILITY OF THE ALPHA PROSPECT- A POTENTIAL $CO_2$ STORAGE SITE IN THE SMEAHEIA AREA, NORTHERN NORTH SEA

Md Jamilur Rahman[1*], Jung Chan Choi[2], Manzar Fawad[1], Nazmul Haque Mondol[1,2]

[1] University of Oslo (UiO), Oslo, Norway
[2] Norwegian Geotechnical Institute (NGI), Oslo, Norway

* Corresponding author e-mail: m.j.rahman@geo.uio.no

## Abstract

$CO_2$ injection into a saline aquifer requires a viable caprock to arrest the vertical movement of the $CO_2$ plume. Quantitative assessment of caprock integrity is often challenging because of uncertainties involved in the model input parameters. In this study, Draupne Formation's reliability as caprock is evaluated before $CO_2$ injection by introducing a stochastic approach. We estimated both deterministic factors of safety and probabilistic failure values of different scenarios, and the results are compared. The probabilistic failure values are calculated using the First Order Reliability Method (FORM). Draupne formation shows a considerably low probability of failure with a high-reliability index in the initial stress condition. The sensitivity study reveals that the pore pressure and horizontal stress are the most crucial parameters and contribute two-thirds to failure probability. When the change of effective horizontal stresses in the reservoir is assumed considering the pore pressure change in the Troll field, this study shows that the field production may decrease the probability of shear failure. Moreover, the study indicates that the suggested probabilistic approach is critical in the presence of various uncertainties. However, the assumptions used in this study, especially the change in effective horizontal stresses within the reservoir, can be affected by other factors (e.g., stiffness contrast between reservoir and surroundings, geometrical effects, stress paths, etc.) and should be investigated further.

***Keywords:*** *Caprock integrity; Caprock Reliability; Probability of failure; Draupne Formation; Smeaheia*

## 1. Introduction

Caprock assessment is a critical parameter in a $CO_2$ storage project because it prevents the vertical migration of fluids out of traps. The top seal commonly consists of fine-grained rocks, which have significantly small pore throat radii compared to the reservoir below and act as an impermeable layer due to exceptionally high capillary entry pressure. However, leakage occurs when the buoyancy pressure exceeds the capillary entry pressure. The capillary breakthrough is highly unlikely when the caprock consists of fine grain particles; instead, mechanical fracturing becomes the primary failure mood while the reservoir's pore pressure approaches the formation fracture strength [1]. The caprock failure risk significantly increases in the $CO_2$ storage project because injecting $CO_2$ into the saline aquifer will increase the reservoir pore pressure and affect the caprock's stress and strength. Therefore, seal strength characterization is necessary to prevent any $CO_2$ leakage risk.

The studied Alpha prospect is located in the Smeaheia area, northern North Sea, and investigated as a potential storage site by Equinor and Gassonova [2]. The main reservoir rocks comprise Upper Jurassic Sognefjord, Fensfjord, and Krossfjord formation sandstones, where the organic-rich Draupne and Heather Formation shales act as a caprock. Because of the significant amount of fine-grained sediments (i.e., clay minerals) in the caprock [3], the capillary breakthrough is very unlikely; hence, the injection-related top seal fracture is one of the main caprock failure risks in the Alpha prospect. However, estimation of caprock mechanical properties (i.e., brittleness) is very complex and uncertain. Moreover, the stress path changes due to injection are mostly unknown in a saline aquifer. In the presence of many uncertainties, the deterministic method of caprock analysis is somewhat questionable [4]; instead, a probabilistic approach is more suitable [5], [6]. Therefore, we conducted a probabilistic analysis to evaluate the Draupne Formation reliability as a caprock using the First Order Reliability Method (FORM). Comparison analysis between deterministic value and probabilistic assessment is also carried out. Moreover, the relative importance of different uncertain parameters is also evaluated. This probabilistic analysis technique for the subsurface structure is a new approach that was recently introduced by Rahman et al. [7] for fault reliability analysis. The hypothetical failure cases are evaluated to identify the reliability failure values to compare them with the in-situ probability of failure values.

## 2. Geologic framework of the study area

The study area experienced two rifting events, possibly during the Permo-Triassic and the Late Jurassic to Mid-Cretaceous times [8]–[10]. A wide basin with deep-rooted faults and thick syn-depositional wedges was centered on the Horda Platform during the 1st rifting event. Several N-S trending faults were formed, which were believed to be rooted in Caledonian zones of crustal weakness [10], demarcating the area's structural elements. The Smeaheia area is bounded by two faults, where the Øygarden Fault Complex (ØFC) delineates the east, and the Vette fault outlines the western boundary shown in Figure 1a. In the Late Jurassic to Mid

Cretaceous time during the 2nd event, rifting and tilting activities shifted westward and assumed that weak stretching with the reactivation of major Permo-Triassic faults on the Horda Platform [8]–[13].

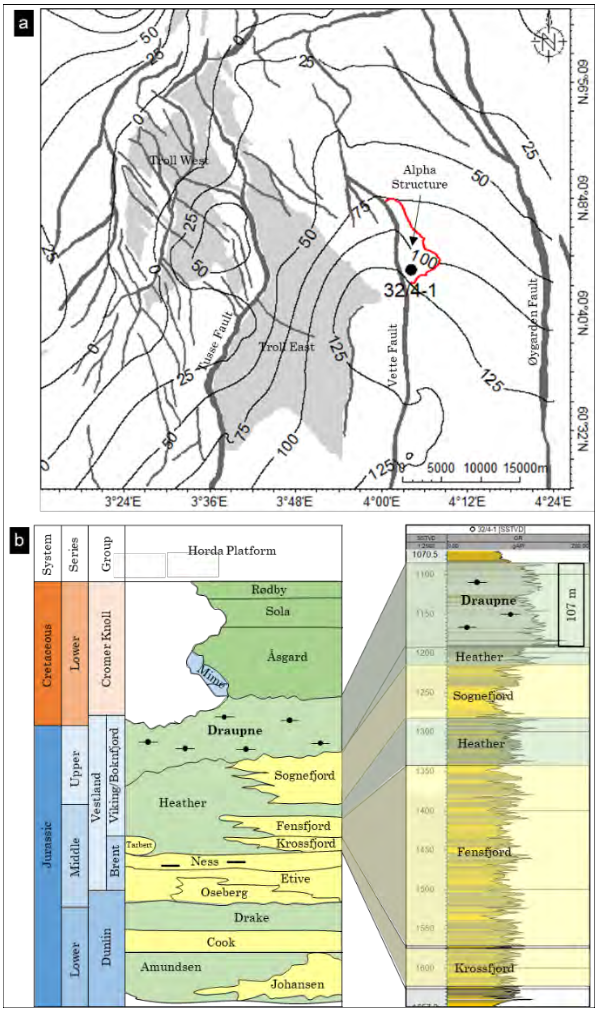

Figure 1: Location map of the Horda Platform showing the major and minor faults with Troll Fields as reference. The contour lines represent the Draupne Formation thickness adapted from [3]. The red polygon against the Vette fault is the Alpha prospect (a). A generalized stratigraphic succession of the Horda Platform showing the Jurassic and Lower Cretaceous formations and the vertical distribution of the Upper Jurassic reservoir-caprock configuration is shown in well 32/4-1 (b).

The primary caprock Draupne Formation shale is part of the Viking Group, deposited in the Late Jurassic syn-rift time within the East Shetland Basin, the Viking Graben, and over the Horda Platform area [2]. The thickness of this formation varies significantly [3], which varies between 75 to 125 m within the Alpha prospect (Fig. 1a), while the well 32/4-1 (Alpha) penetrates 107 m thick Draupne shale. The formation consists of dark grey-brown to black, non-calcareous, carbonaceous, occasionally fissile claystone deposited in an open marine environment with restricted bottom circulation and often with anaerobic conditions [14]. It is also characterized by high gamma-ray values (usually above 100 API) due to high Uranium and TOC content. Interbedded sandstone and siltstone, as well as minor limestone streaks and concretions, are also present. Draupne Formation generally has a diachronous contact with the Heather Formation in the lower boundary. However, on the northern Horda Platform, Late Jurassic sandstones of the Sognefjord Formation mark the base of the Draupne Formation. The upper boundary of the Draupne Formation is usually characterized by Cretaceous rock (Cromer Knoll Group), which has a higher velocity and lower gamma-ray response than the over and underlying rocks [15] (Fig. 1b).

## 3. Material and Method

Caprock structural reliability depends on the mechanical properties of that layer and the stress state of the area. Mohr-Coulomb failure criterion approach can evaluate caprock stability. This study assesses the Draupne caprock probability of failure by an analytical model defined by the Mohr-Coulomb failure criterion. The corresponding deterministic factor of safety values is also estimated for comparison.

### *3.1 Model parameters*

The recent study suggested that a normal faulting regime with isotropic horizontal stress conditions is a reasonable stress model for the Alpha prospect [16]. Moreover, the extended leak-off test data in the studied area reveal that the vertical stress gradient is significantly higher than the horizontal stress, reflecting a normal faulting regime (Fig. 2). Therefore, the normal faulting with isotropic horizontal stress conditions was used in this study. The hydrostatic pressure gradient shown in Figure 2 was calculated using the depth profile from well 32/4-1 drilled in the Alpha prospect. However, the vertical and horizontal stress profiles were estimated using the extended leak-off test (XLOT) data scouted from the Statoil Underground report [17].

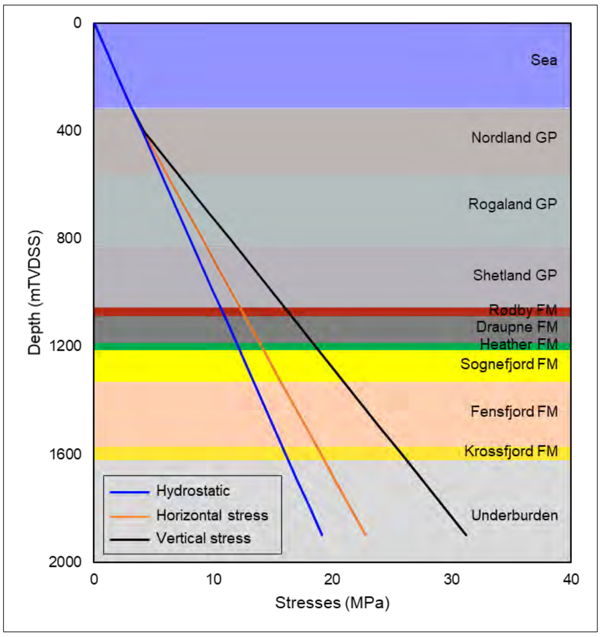


Figure 2: In-situ stress profile for the Alpha structure calculated using extended leak-off test (XLOT) data [17] indicating normal faulting regime with isotropic horizontal stress condition (adapted from [7]).

This study only focuses on the in-situ stress condition, and the dynamic $CO_2$ injection effect is not considered. However, the pore pressure depletion scenario due to the possible communication with the hydrocarbon production in the Troll Field was analyzed. Maximum 4 MPa depletion estimated by the Statoil studies was used as a case in this modeling work. However, we did not consider any stress path changes while running that scenario.

Moreover, the theoretical failure scenario was analyzed to get a quantitative estimation of probability failure values compared to real cases. The caprock failure scenario was estimated by decreasing horizontal stress while the other parameters (i.e., vertical stress and pore pressure) remain in the initial condition. A summary of all cases is shown in Table 1, which were evaluated to estimate the Draupne caprock probability of failure.

Table 1: Various caprock scenarios tested in this study.

| | Assumptions |
|---|---|
| Case-1 | Initial stress condition |
| Case-2 | Depletion due oil/gas production from Troll |
| Case-3 | Caprock failure due to decreasing $\sigma_3$ |

The Mohr-Coulomb plots of the Draupne Formation for three cases are shown in Figure 3. The initial state stress condition (case-1) represents a relatively large distance between the Mohr circle, and Coulomb failure (Fig. 3a). The pore pressure depletion scenario (case-2) further shifts the circle away from the envelope by increasing the effective stresses (Fig. 3b). Moreover, the theoretical caprock failure plots show that the case-3 shear failure occurs at $55^0$ $\sigma_1$ plane (Fig. 3c). The theoretical caprock failure value for case-3 ($\sigma_h^3$) is estimated using the MohrPlotter software by selecting 'failure by horizontal stress' mode, and the horizontal stress value estimated was 10.57 MPa when the shear failure occurs.

The laboratory test result of rock strength parameters (i.e., cohesion and friction angle) of the Draupne Formation were scouted [16]–[20] and also estimated from the wireline log. The compressional velocity ($V_p$) based empirical equation proposed by Horsrud [19] was used, which stated that:

$$C_0 = 0.77V_p^{2.93} \quad (\Phi = 30 - 55\%), \tag{1}$$

where $C_0$ is compressional strength in MPa and $V_p$ is in km/s.

In the model, the input parameters used are shown in Table 2. It should be noted that statistical information in the table is from a limited database and should only be used to test the methodology. It may represent the field condition. Five random variables such as vertical stress ($\sigma_v$), horizontal stress ($\sigma_h$), pore pressure ($P_p$), cohesion ($S_0$), and friction angle ($\phi$) are used to run the stochastic model where arithmetic average with standard deviation was used to define the ranges. However, for additional properties of case-2 and case-3 (i.e., $P_p^2$ & $\sigma_h^3$), the same standard deviation (i.e., like case-1) value was used (Table 2).

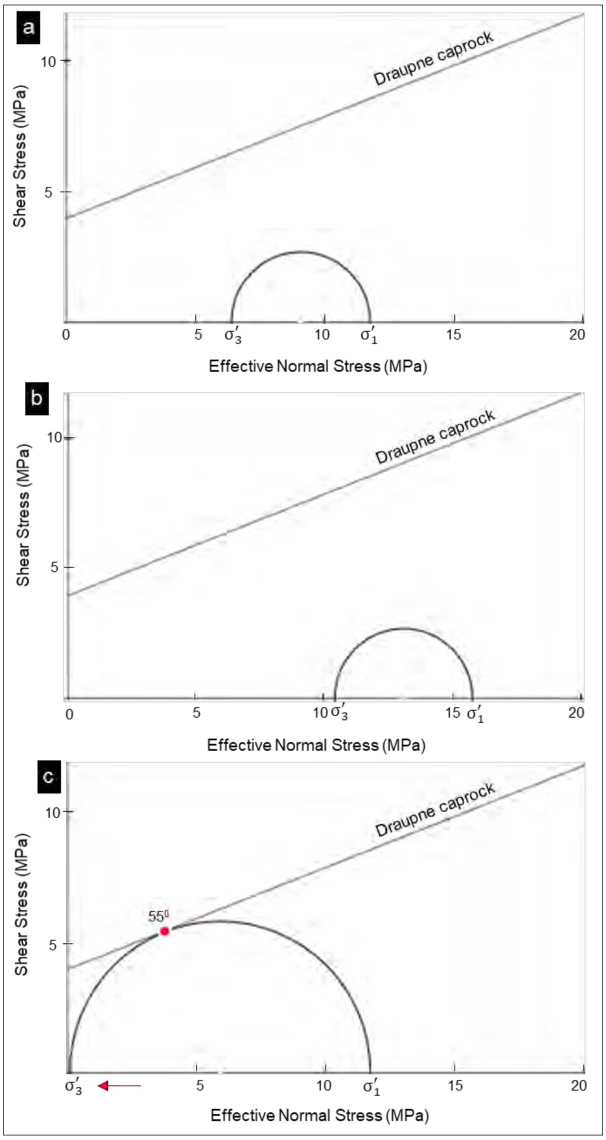


Figure 3: Mohr-Columb plots with Draupne Formation failure surface: (a) initial reservoir stress state condition (case-1), (b) depleted scenario due to oil/gas production from Troll (case-2), and (c) shear failure scenario due to decreasing $\sigma_3$ (case-3).

Table 2: Input parameters for the model with the type of distribution and data sources. The superscript numbers in the parameters name represent as case numbers. Note the statistical information in this table is based on a limited database and should be used only to test the methodology. It may not represent the field conditions.

| Parameters | Average | Unit | Standard Deviation | Distribution |
|---|---|---|---|---|
| $\sigma_v$ | 22.25 | MPa | 0.65 | Normal |
| $\sigma_h^{1,2}$ | 16.85 | MPa | 0.95 | Normal |
| $\sigma_h^3$ | 10.57 | MPa | 0.95 | Normal |
| $P_p^{1,3}$ | 10.48 | MPa | 1.32 | Normal |
| $P_p^2$ | 6.48 | MPa | 1.32 | Normal |
| $S_0$ | 3.93 | MPa | 1.05 | Log-Normal |
| $\phi$ | 21.63 | Degree | 5.14 | Normal |

Standard deviation can indicate the data spread and might serve as a measure of uncertainty. For example, a small standard deviation value indicates clustered closely around the mean with more precision and vice versa. Moreover, most geological processes follow a normal or log-normal law [5]; thus, we assumed normal distribution for most of the properties except caprock cohesion in this study. A log-normal distribution was used for caprock cohesion assuming the parameter cannot be physically negative within three standard deviations of average.

### *3.2 Model definition*

The reliability of a structural component depends on the uncertainties in load (S) and resistance (R), and if both are normally distributed, the failure probability might be assessed directly by the safety margin M and denoted as:

$$M = R - S, \tag{2}$$

and the probability of failure may be assessed through:

$$P_f = P(R - S \leq 0) = P(M \leq 0), \tag{3}$$

where M is normally distributed with parameters with the mean $\mu_M = \mu_R - \mu_S$ and standard deviation $\sigma_M = \sqrt{\sigma_R^2 + \sigma_S^2}$. The failure probability may be determined by the use of the standard normal distribution function as:

$$P_f = \Phi\left(\frac{0-\mu_M}{\sigma_M}\right) = \Phi(-\beta), \tag{4}$$

where $\mu_M/\sigma_M = \beta$ is called the safety/reliability index, which is the standard deviation by which the mean value of the safety margin M exceeds zero or most likely exceeds the failure point (Fig. 4a). However, if the resistance and the load cannot be described by only two random variables but rather by functions of the same random variables and statistically dependent, the safety margin M will be:

$$M = R - S = f_1(X) - f_2(X) = g(X), \tag{5}$$

where X is a vector with n so-called basic random variables, the function g(X) is denoted as the limit state function, which is a boundary between desired (g(X) >0) and undesired (g(X) ≤ 0) performance of any structure and defined within a mathematical model for functionality and performance [21]. In this study, the Mohr-Coulomb failure criteria-based limit state function was considered. Assuming isotropic horizontal stress condition within a normal faulting regime, the factor of safety (FoS) is defined as:

$$FoS = \frac{\left[\left(\frac{\sigma_1' + \sigma_3'}{2}\right) + \frac{S_0}{\tan\phi}\right]\sin\phi}{\frac{\sigma_1' - \sigma_3'}{2}}, \tag{6}$$

$$\sigma_1' = \sigma_1 - p_p, \tag{7}$$

$$\sigma_3' = \sigma_3 - p_p, \tag{8}$$

where, $\sigma_1'$ is effective vertical stress, $\sigma_1$ is vertical stress, $\sigma_3'$ is effective horizontal stress, $\sigma_3$ is horizontal stress, $p_p$ is pore pressure, $S_0$ is cohesion, and $\phi$ is friction angle.

The state of the structure is safe when the factor of safety is greater than 1 and fails when it is less than 1. Therefore, the limit-state function defines as:

$$g(x) = FoS - 1, \tag{9}$$

where, g(x) is the limit-state function which is the boundary between safe (g(x) >0) and failure (g(x) ≤ 0) state.

The First Order Reliability Model (FORM) was used to estimate the failure probability of Draupne caprock. This method was proposed by Hasofer and Lind [22] and widely used in practical engineering problems [6], [23]. This method linearizes the failure surface (g(z)) at a design point z* where the shortest distance is called the reliability index (β) and normal vector direction to the failure surface denoted as α (Fig. 4c). However, the inaccurate result could be estimated if the linearization design points are not correctly selected. Moreover, the reliability index value is also used as a performance indicator and directional vector to describe the random variables' relative importance. We analyzed this sensitivity factor to identify the significance of each parameter used in the model.

The Python-based open-source structural reliability analysis module PyRe [24] was used to initiate and run the FORM models. PyRe has been created using the core function of the Finite Element Reliability Using Matlab (FERUM) project, which is very flexible and extensive, making it applicable to a large number of problems. Other software such as MohrPlotter version-3 and Excel 2016 were also used for the Mohr-Coulomb plot and sensitivity plots, respectively.

The probabilistic reliability analyses deal with the structural uncertainties, provide a rational framework, and have a different approach than the deterministic estimation [6]. Although the failure probability approach is widely used for engineering purposes, it is new for caprock characterization. Therefore, a comparison between deterministic safety factors with the probability of failure was also analyzed. Such a comparison will help to understand caprock failure probability values.

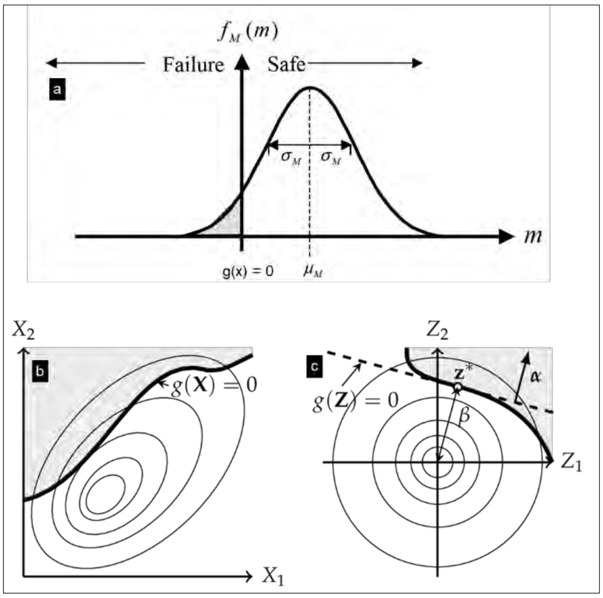


Figure 4: Structural reliability concept and model definition: (a) Gaussian distribution of the probability distribution function of safety margin M showing the failure and safe events modified after Faber [23], (b) limit state function g(X) stated in the physical space using two random variables ($X_1$ and $X_2$), and (c) after normalizing the random variables into standardized normally distributed variable ($Z_1$ and $Z_2$) with the design point z* and reliability index β. Note that the grey shaded area denoted the failure domain (modified after Madsen et al., [25]).

## 4. Results

The deterministic and probabilistic failure values with corresponding reliability index (β) are summarized in Table 3. In the in-situ stress condition (case-1), the Draupne Formation probability of failure (PoF) is 1.38E-08, while the factor of safety (FoS) shows a value of 2.60. However, the depleted scenario (case-2) due to Troll Field production decreases the failure probability number (<3.0E-08). The safety factor also increases from 2.60 to 3.16. Although the FoS increases from case-1 to case-2, the increase is not significant compared to PoF. Moreover, the reliability index value also increases from case-1 to case-2. The FoS for theoretical shear failure scenario (case-3) shows caprock failure by representing a value=1. The corresponding PoF and β value showed 2.42E-02 and 1.97, respectively.

Table 3: Deterministic factor of safety (FoS) and the probability of failure (PoF) of different cases. Corresponding reliability index (β) values are also shown.

| | FoS | PoF | β |
|---|---|---|---|
| Case-1 | 2.60 | 1.38E-08 | 5.56 |
| Case-2 | 3.16 | <3.0E-08 | <5.0 |
| Case-3 | 1.00 | 2.42E-02 | 1.97 |

The comparative analysis between deterministic and probabilistic sensitivity gives a unique opportunity to explain the reliability of the proposed method (i.e., FORM). The deterministic sensitivity was estimated using the 'one variable at a time' (OVAT) technique [26], [27], where each input parameter is alternatively assigned its minimum and maximum values when the other parameters are fixed to their mean values. The parameters ranges used are summarized in Table 4.

The tornado diagram of case-1 (Fig. 5) illustrated that the initial horizontal stress ($\sigma_h^1$) has the most significant impact on the factor of safety than the rest of the input parameters. Moreover, initial vertical stress ($\sigma_v$) and Cohesion ($S_0$) have significant influences.

Table 4: Minimum and maximum values used in the deterministic sensitivity analysis.

| Parameter | Value Range |
|---|---|
| Initial vertical stress ($\sigma_v$) | 21.60 - 22.90 (MPa) |
| Initial horizontal stress ($\sigma_h^1$) | 15.90 - 17.80 (MPa) |
| Pore Pressure ($P_p^1$) | 9.16 - 11.80 (MPa) |
| Cohesion ($S_0$) | 2.88 - 4.98 (MPa) |
| Friction angle (ϕ) | 16.49 - 26.77$^0$ |

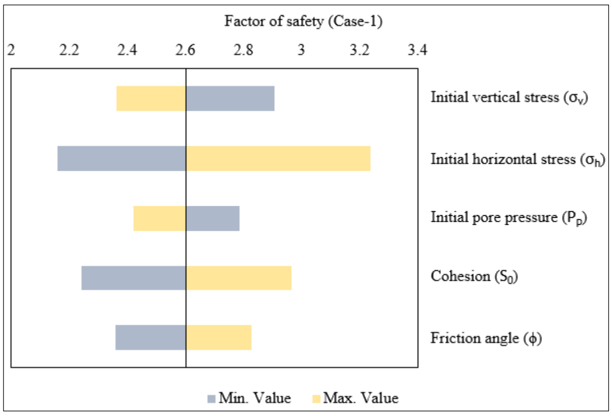


Figure 5: The tornado diagram of the case-1 scenario illustrated the relative importance of the input parameters.

The relative design sensitivity factor or the relative importance factors (α) are often referred to as probabilistic sensitivity and indicate the effect of each parameter on the reliability function [28]. This is very useful for the ranking of random variables and obtained by performing several probabilistic analyses and treating every individual parameter as a deterministic variable in each study [29], [30]. A positive value indicates a direct relationship between the variable's value and the response, while a negative sensitivity suggests an inverse relation. However, the square of each sensitivity factor ($\alpha_i^2$) is a measure of its contribution to the probability, and the sum is equal to 1. The relation between the input parameters with the probabilistic response is illustrated in Figure 6, where pore pressure and friction angle show a direct connection with the result, and horizontal stress and cohesion suggested an inverse relation. However, the vertical stress showed a significantly low positive value (approximately zero) and indicated insignificance contribution during the calculating probability of failure.

Figure 7 display the relative contribution of each input parameter within different cases. The failure probability using the FORM technique mainly depends on the horizontal stress, pore pressure, and cohesion, in which pore pressure is the most significant. A substantial pore pressure influence was observed in case-2 (i.e., 60%), which is a depleted scenario due to Troll Field production. A gentle contribution of friction angle is illustrated in case-1; however, there is very little impact in the rest of the cases.

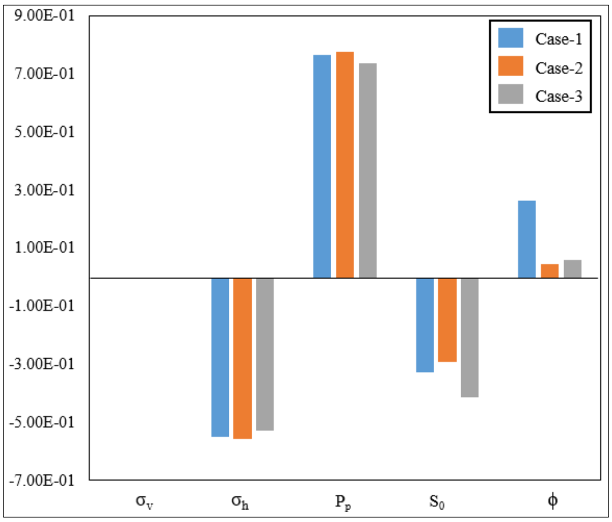


Figure 6: Sensitivity factor ($\alpha$) in the probabilistic analysis of Draupne Caprock shale using FORM showing the relations between random input variables and the responses.

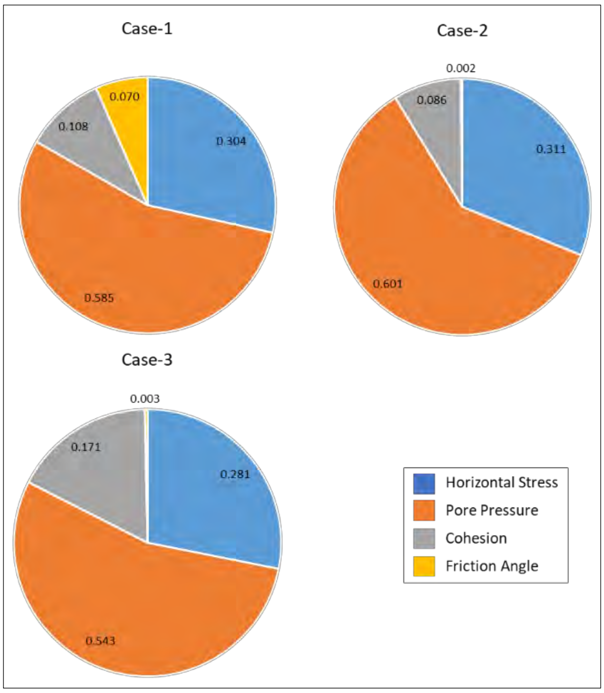


Figure 7: Square of each factor ($\alpha^2$) showing the contribution variation to the probability failure analysis within different cases.

## 5. Discussion

The input parameters used for caprock failure analysis are often highly uncertain, and the deterministic safety factor does not reflect the corresponding failure probability [6]. The approach used in this study can integrate all the possible uncertainties by adding the ranges and probabilistically estimating the structural reliability. For example, case-2 failure probability significantly decreases the chances of failure compared to case-1, while the increase of safety factor is insignificant (i.e., from 2.6 to 3.16). Therefore, the probabilistic reliability analysis for subsurface structures could be a useful tool to incorporate the parameter uncertainties and quantify the failure risks. However, the probabilistic method is susceptible to the input parameter ranges and should be defined very carefully. For instance, in this analysis, the standard deviation value defined for $\sigma_v$ and $\sigma_h$ is only 3% and 6% of the average value, indicating these properties are not very sensitive and lead to a significantly low PoF, and $\beta$ value (Table 3). Moreover, the insignificance relative contribution of $\sigma_v$ might be the effect of the uncertainty range. Therefore, the emphasis is needed to define the uncertain parameters range before use as an input parameter in the failure probability model.

The reliability index and probability of failure in any structure are a relative measurement of the current condition and provide a qualitative estimation of the expected performance [31]. However, integrity analysis of caprocks presents under certain pressure, and temperature conditions are very complex. Although our modeling approach considers various pressure conditions, the temperature effect on caprock mechanical behavior is beyond the scope. Moreover, the variation between the deterministic and probabilistic sensitivity indicates that further analysis is needed to examine the method's reliability. The model used in this study is a novel approach for caprock failure characterization; hence, there are no published charts for standard. However, this method is widely used in geotechnical engineering, and we compare our result with the expected performance range for embankment shown in Table 5 [31]. According to the chart, the in-situ condition (case-1) and depleted scenarios (case-2) are above the highest performance level (High). However, the theoretical failure case does not represent the same reliability index value and is classified as Poor (case-3). The probability of unsatisfactory performance illustrated that for case-3, 24 of every 1000 would result in a failure event. The failure events are significantly different from the theoretical failure due to decreased horizontal stress and pore pressure changes. However, the unsatisfactory performance number of the in-situ stress scenario (case-1) is only 13 out of $10^9$ runs, making this case safer.

Table 5: The defined performance level with corresponding unsatisfactory events and reliability index values adapted from U.S. Army Corps of Engineers [31].

| Expected Performance Level | Probability of Unsatisfactory Performance | Reliability Index ($\beta$) |
|---|---|---|
| High | 0.0000003 | 5.0 |
| Good | 0.00003 | 4.0 |
| Above average | 0.001 | 3.0 |
| Below average | 0.006 | 2.5 |
| Poor | 0.023 | 2.0 |
| Unsatisfactory | 0.07 | 1.5 |
| Hazardous | 0.16 | 1.0 |

## 6. Conclusion

The probabilistic estimation of the Draupne Formation caprock's reliability is the critical condition for a successful Alpha prospect $CO_2$ injection site. This study's outcomes proved to be a valuable approach when several uncertainties are present. However, it needs a careful investigation to define the parameter ranges before using them as model input. The main observations of this study are as follows:

- In the initial condition, the reliability of Draupne caprock shales is excellent, with a very low chance of mechanical failure. Moreover, considering the Troll Field depletion scenarios, the failure probability decreases significantly.
- Pore pressure and friction angle directly relate to the probabilistic response, while horizontal stress and cohesion have an inverse relation. Overall, pore pressure and horizontal stress are the main contributors to the probability of failure value.
- Although there is a similar increasing or decreasing trend between deterministic and probabilistic values of different cases, the variations are significant in the probabilistic approach.

This study indicates that the Draupne Formation can be a safety barrier during $CO_2$ injection into the Alpha prospect. Nevertheless, it should be perceived that this study has focused on the feasibility of the methodology rather than the field evaluation. The injection-related potential risks can be affected by other factors (e.g., stiffness contrast between reservoir and surroundings, geometrical effects, drainage condition, stress paths, etc.) and need to be evaluated further with a better assessment of the statistical input and the numerical simulation.

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