Modeling Approach Provides Optimal Retrieval Time to Minimize Core Decompression Damage

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***Abstract**: In the oil and gas industry rock samples are routinely retrieved from the subsurface using a technique called coring. Detailed physical measurements of the core in a controlled laboratory setting can determine geomechanical and flow properties. Consequently, it is important to retrieve the core from depth without avoidable damage. Core integrity can be compromised when the core is retrieved too quickly without allowing sufficient time for pore pressure equalization. Core integrity is particularly important in low-permeability shale formations, which suggests long core retrieval times. Operational considerations, on the other hand, demand the shortest possible retrieval times.*

This paper presents a resolution to the challenge of finding the best core retrieval time by using Abaqus and Isight. A core retrieval effort is described by modeling an axisymmetric, finite-element representation of a core with pore fluid that is subjected to successively decreasing external pore-pressure boundary conditions and pressure loads. The modeling results are analyzed for the maximum pore-pressure difference and compared with rock strength criteria to predict potential core damage. The technique uses Isight to obtain the optimal retrieval time for given geometric and material parameters.

The approach is invaluable for coring in low-permeability shale formations because the operational experience of coring in permeable sandstone formations is not applicable. The combined use of Abaqus and Isight in a reliability study enables core damage probability to be determined. In addition, the technique provides an analytical-based guideline for the shortest core-retrieval time without compromising core quality due to decompression.

***Keywords**: Geomechanics, Optimization, Reliability.*

1. Introduction

In coring operations, rock samples are removed from the subsurface so they can be analyzed in detail in a laboratory. Results from the measurements typically influence important and capital-intensive decisions. It is therefore vital to retrieve high-quality core samples and to avoid any damage to the core samples where possible. One common, but avoidable, source of core sample damage is related to decompression and occurs when the pore fluid in the core sample does not have sufficient time to equilibrate to the decreasing external pressure conditions during ascension (Zubizarreta et al, 2011). Core damage from decompression is a particular concern in tight shale formations in which permeability can be several orders of magnitudes lower than in conventional siltstone or sandstone formations, because the characteristic pressure equilibration time increases with decreasing permeability (Hettema et al., 2002). Therefore, the coring engineer must plan for a slower core sample ascent in low-permeability formations. Unfortunately, the abundant experience gained in conventional plays is not directly applicable, and the typical advice in practice, lacking an analytical-based estimate, to “retrieve slowly” does not always yield acceptable results. The dilemma of choosing a retrieval speed is further complicated by cost considerations that favor a short retrieval time to minimize operational expenses.

A method to determine a core retrieval speed that is sufficiently slow to avoid core damage from decompression and at the same time as fast as possible to minimize operational expenses is a valuable tool. In conventional, high-permeability applications it can be used to assess whether experience-based retrieval speeds are near optimal or if they can be safely increased for operational cost savings. In unconventional, low-permeability applications such a method may be the only way to objectively obtain an estimate for an optimal retrieval speed.

This paper presents how the use of Abaqus and Isight can provide a guideline for selecting the optimum core sample retrieval time. Abaqus is used to model an axisymmetric core sample with pore fluid that is subjected to successively decreasing external pore-pressure boundary conditions and pressure loads. For successful core retrieval, the maximum pore pressure difference in the core sample must not exceed a given rock strength criteria. Isight is used to obtain the optimum retrieval time to satisfy the pore pressure constraint while minimizing the total retrieval time for constant material parameters. For a more realistic scenario in which a key parameter is expected to be randomly distributed, Isight is used to quantify the probability of success for the previously identified optimum retrieval time, and to estimate a new tripping time that has a 90 % probability of success. Furthermore this paper presents how to quantify the variability of input parameters (permeability and fluid viscosity).

2. Methods

2.1 Finite-element modeling of a core sample during retrieval from the subsurface

The finite-element method is used to model a core sample with pore fluid that is subjected to successively decreasing external pressure loads and pore pressure boundary conditions. The initial pore pressure is assumed to be equal to the hydrostatic pressure of the drilling fluid column. Pore fluid is allowed to leak out as the external pressure decreases. However, the confining pressure on the core may become smaller than the pore pressure in the core which can lead to sufficiently large pressure differences to cause core damage. This paper examines the onset of core damage and does not explicitly model core damage (such as the generation or propagation of fractures and fluid pathways or damage evolution). Instead the maximum pore pressure difference between the inside of the core sample and the confining pressure during core ascent is compared with a rock strength criterion (i.e., tensile rock strength) in a post-processing routine to identify whether core damage from decompression is expected.

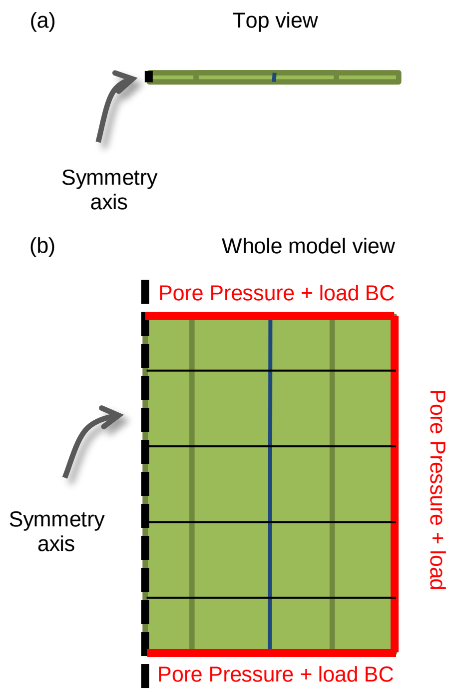

Figure 1. Schematic of an axisymmetric FEA model. (a) Top view. (b) Whole model view.

Figure 1 shows a schematic representation of the model. The assumption of isotropy is sensible given the uncertainties of many parameters for typical applications, and suggests to using an axisymmetric model. The finite-element solution for an axisymmetric model can be computed quickly compared to a 3D model. If desired, however, the present model can be replaced by a 3D model with the remainder of the workflow remaining unchanged.

Figure 2 shows a realization of the axisymmetric model using CAX8P elements. The center image shows the upper part of the model domain. The image to the left is a swept 3D view of the model. The image to the right shows the pore pressure drop across a radial profile across the center of the core when the core is near the surface and most of the pore fluid is bled off.

The original axisymmetric model was created with Abaqus/CAE and written to an input file. Subsequent modifications to the input deck were performed manually or with scripts. The model can be used to predict whether a proposed retrieval speed leads to core decompression damage. In addition to a constant retrieval speed, a retrieval schedule comprising different speeds at different depths can be employed. A script uses the proposed retrieval schedule in combination with other input parameters (e.g., coring depth and drilling fluid density) to compute an amplitude function, which describes how the pressure on the outside of the core successively decreases with time. The

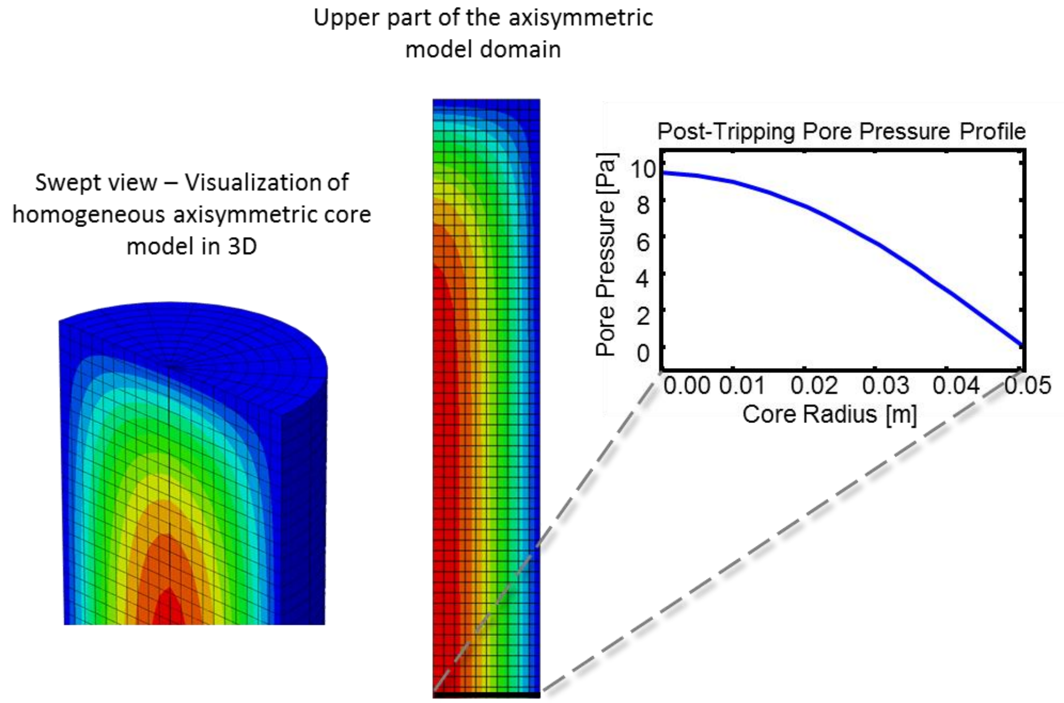

Figure 2. Realization of the axisymmetric model.

amplitude function is used to define boundary conditions and loads when simulating the ascending core sample.

A workflow of modifying a proposed retrieval speed manually and performing iterative testing until an acceptable speed is identified consists of the following steps, most of which are automated and only require minimal input from the user.

1. Adjust FEA model to geometry parameters (core diameter, core length, depth).
2. Create core retrieval schedule (retrieval speed versus depth data points).
3. Set initial conditions (pore pressure, stress) and material parameters (e.g., permeability).
4. Compute amplitude (pressure versus time; used for external boundary condition and load).
5. Perform analysis with Abaqus/Standard.
6. Post-process using in-house scripts (extract pore pressure profile along center radius; extract maximum and minimum pore pressure versus time; create XY plots).
7. Compare maximum pore pressure difference to tensile rock strength.
8. Iterate with various proposed retrieval schedules until acceptable schedule is found.

Table 1. Geometric and material parameters.

Geometric parameter	Value
Core diameter Core length Depth (TVD)	0.1 m (4 in) 1 m 3000 m
Material properties (Rock)	**Value**
Permeability Porosity (void ratio) Rock bulk modulus Tensile rock strength Young's modulus Poisson's ratio	9.869×10^{-21} m^2 – 9.869×10^{-19} m^2 (10^{-5} mDarcy – 10^{-3} mDarcy) 0.15 5 GPa 3 MPa 9 GPa 0.2
Material properties (Fluid/Gas)	**Value**
Fluid kinematic viscosity Fluid specific weight Fluid dynamic viscosity Fluid bulk modulus	3.6×10^{-7} m^2/s 10^4 N/m^3 3.7×10^{-4} Pa s (0.37 centipoise) 1 GPa
Material properties (Drilling fluid)	**Value**
Drilling fluid density	1.6×10^3 kg/m^3 (1.6 SG)

Unless otherwise specified the parameters listed in Table 1 remain constant for the purpose of the paper. The model is applicable to smaller cores (e.g., side wall cores) when geometric parameters are adjusted. Hydraulic conductivity, which is used as an input parameter for the `*PERMEABILITY` keyword, can be computed as

$$K = k\,\frac{g}{\mu} = k\,\frac{g\,\rho}{\nu}, \tag{1}$$

where k is permeability, g is acceleration due to gravity, μ is kinematic viscosity, is ν dynamic viscosity, and ρ is fluid density.

Iterating through the above steps with various retrieval schedules manually can be instructive and educational. However, practice often demands identifying the shortest retrieval time for which no core damage from decompression is predicted without much user intervention. This is a classic optimization problem that can be solved using Isight.

2.2 Approximation

Calculator components are placed on input and output sides of the Abaqus component. All three components are encapsulated into a finite-element analysis (FEA) task, which together with additional unit conversion components form a second task. Figure 3 shows the corresponding sim-flow diagram. Variable input parameters are total retrieval time and hydraulic conductivity. The response is defined as the maximum pore pressure difference across the center radius of the model.

To save computing time later, an approximation of the FEA component was created using the linear elliptical basis function technique. 100 execution design points are chosen with randomly distributed input parameters from previous executions; total retrieval time varied from 7200 s to 172800 s (2 hours – 2 days) and hydraulic conductivity varied between $10^{-14}\mathrm{m/s}$ and $10^{-11}\ \mathrm{m/s}$. Figure 4 shows the design space. A cross-validation error analysis method is used on all design points. Figure 5 shows the error analysis, for which the average error is 0.5 % and the maximum error is 10.2 %. Figure 6 shows the response surface defined by the maximum pore pressure difference.

2.4 Variable retrieval speeds

A variable retrieval speed scenario can be modeled with a piecewise constant retrieval speed scenario by introducing into the sim-flow a loop over N steps. In each step the optimum retrieval speed is identified for a segment with a length of $1/N$ of the total path length through the subsurface. The restart option in Abaqus is used to apply output data from a previous step as initial conditions for field variables the subsequent step. In this paper $N = 10$. The constant retrieval speed is used as initial guess for the optimization method.

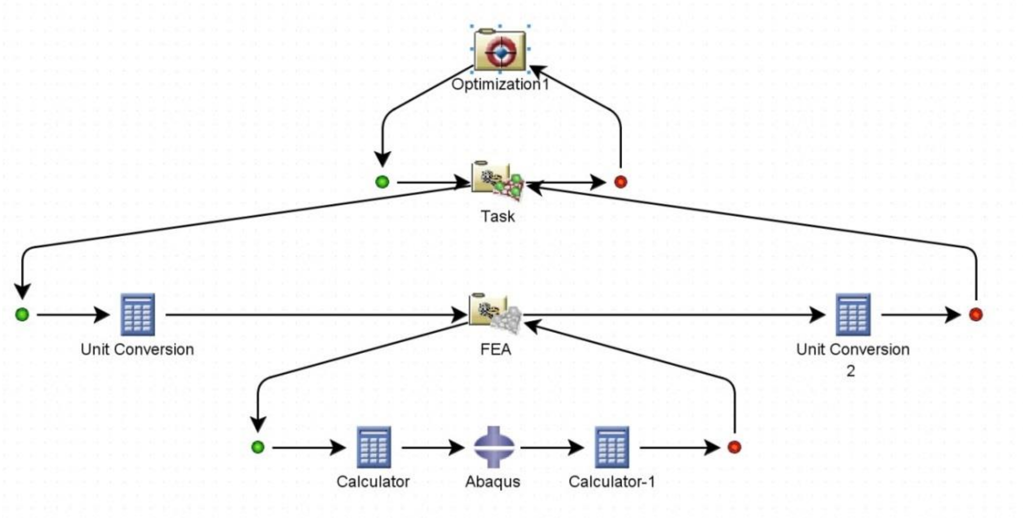

Figure 3. Sim-flow diagram for optimization.

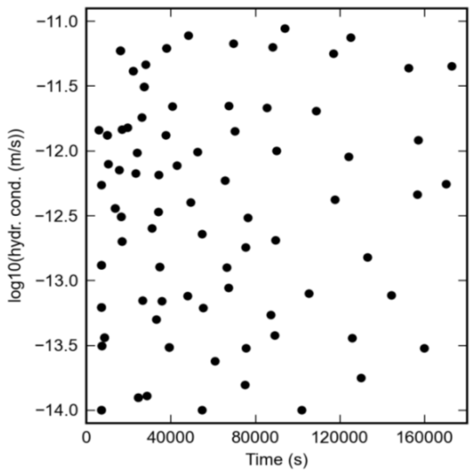

Figure 4. Approximation design data points.

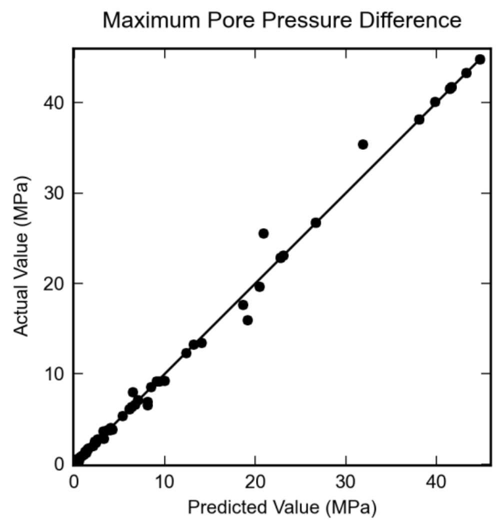

Figure 5. Approximation error analysis.

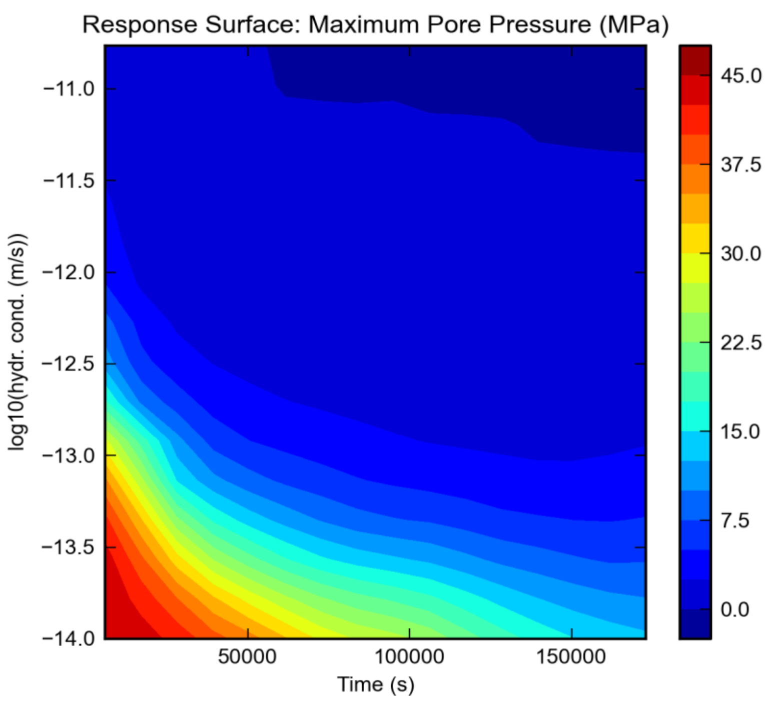

Figure 6. Approximation response surface.

2.5 Variability analysis of permeability and viscosity

Whereas the key parameter in the Abaqus analysis is hydraulic conductivity, typical variables in the oil- and gas industry include permeability and viscosity. Equation 1 can be used to compute hydraulic conductivity from permeability and viscosity. In applications, in particular in tight shale formations, uncertainty in permeability is typically much larger than the uncertainty in viscosity. It is useful, therefore, to delineate the influence of variability in permeability and viscosity.

One way to quantify the variability uses a carpet plot, where permeability and viscosity are independent inputs and the maximum pore pressure difference within the core sample is the output. A carpet plot is employed based on the Six Sigma component for the constant optimum time with a full factorial design of experiments technique. A radial base function approximation is selected as fitting method where the z-values are clipped to the actual data range.

3. Results

3.1 Axisymmetric finite-element model

A proof of concept study was performed to verify the axisymmetric model. Permeability is a key material parameter, and retrieval speeds are of particular concern in tight formations with low permeability. A permeability of 10^{-20} m^2 (10^{-5} mDarcy) was used, which is representative of shales. The retrieval schedule is specified by data point pairs of retrieval speed and depth. From these data pairs the pre-processor can compute flat, step-wise or smooth schedules depending on user input. Figure 7 shows a possible retrieval schedule and the resulting amplitude function; it also shows the corresponding evolution of maximum and minimum pore pressure and of the maximum pore pressure difference within the core sample. Comparing the maximum pore pressure difference with the threshold value given by the tensile rock strength suggests that decompression damage is likely to occur for the proposed retrieval schedule. To avoid core damage, a revised schedule with reduced speeds must be tested. Figure 8 shows such a revised schedule and corresponding amplitude function, and the resulting pore pressure evolution. With the revised schedule, the maximum pore-pressure difference approaches, but does not significantly exceed, the selected rock strength criterion. However, the total retrieval time increases from the previous 15830 s (4.4 hours) to 104370 s (29 hours). Figure 8d suggests the possibility of increasing the retrieval speed at later times. Figure 9 shows a second revision with higher retrieval speeds during the later stages. The second revision predicts that pore-pressure differences remain at or below the rock strength criterion and the total retrieval time decreases more than 2.8-fold to 37500 s (10.4 hours).

The axisymmetric model is useful to predict potential core damage for a given number of proposed retrieval schedules when assuming constant material parameters. However, practical applications often demand finding an optimum retrieval speed with little user intervention, which indicates a need for an automated optimization.

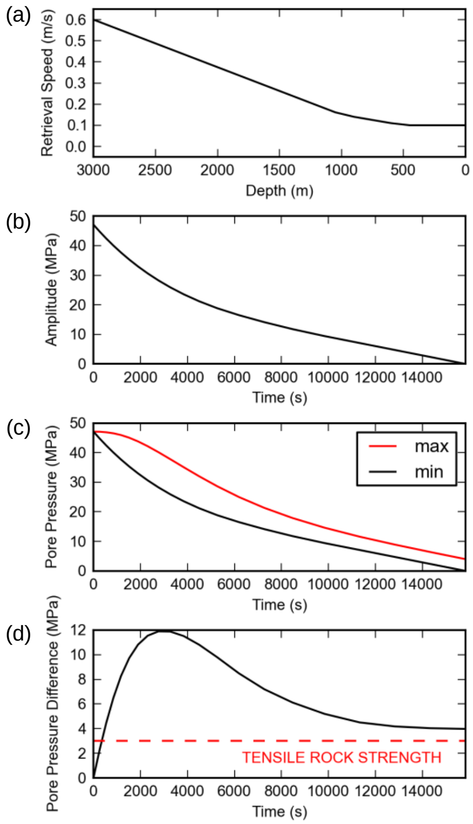

Figure 7. (a) Retrieval schedule and (b) resulting amplitude function. (c) Evolution of maximum and minimum pore pressure. (d) Maximum pore pressure difference within the core sample and tensile rock strength.

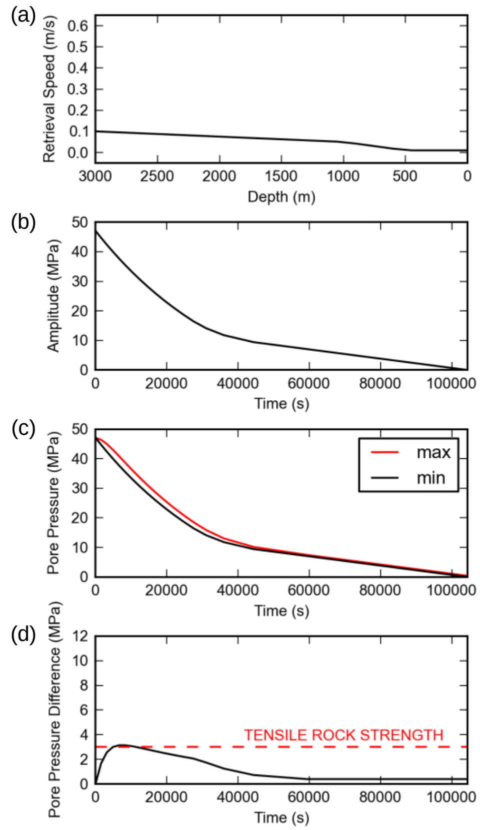

Figure 8. (a) Retrieval schedule and (b) resulting amplitude function. (c) Evolution of maximum and minimum pore pressure. (d) Maximum pore pressure difference within the core sample and tensile rock strength.

3.2 Optimization: shortest retrieval time for which no core damage is predicted

To replace the manual creation of proposed retrieval schedules, the optimization component in Isight was employed on the Approximation. The NLPWL optimization technique was selected with the constraint that the maximum pore pressure difference remains below a threshold value, the tensile rock strength, 3 MPa. A constant hydraulic conductivity of $10^{-12.6}$ m/s was used, which is consistent with the previously discussed cases. Time was initialized with the lowest value from the approximation design points, 7200 s (2 hours). The optimum total retrieval time is identified as 40310 s (11.2 hours). This is in good agreement with the time obtained from the second manually revised schedule discussed above.

3.3 Six Sigma reliability study for cases in which input parameters are not known exactly

In practical applications not all parameters are known exactly and key parameters such as hydraulic conductivity are known only within bounds due to natural variations. Therefore, the Six Sigma reliability component in Isight was used to assess the probability of successful core retrieval. The linear mean value reliability method was used with a lognormal distribution of hydraulic conductivity values with a mean of $10^{-12.5}$ $\mathrm{m/s}$ and a standard deviation of $10^{0.5}$ $\mathrm{m/s}$, and truncated distribution tails at 10^{-14} $\mathrm{m/s}$ and 10^{-11} $\mathrm{m/s}$. The response function was specified by lower and upper limits for the maximum pore pressure difference, 0 MPa and the tensile rock strength, respectively. The probability that core damage from decompression does not occur is 57.7 %, which is below the acceptable level. The next step, therefore, is identifying a retrieval time for which the probability of success is at or above a specific percentage.

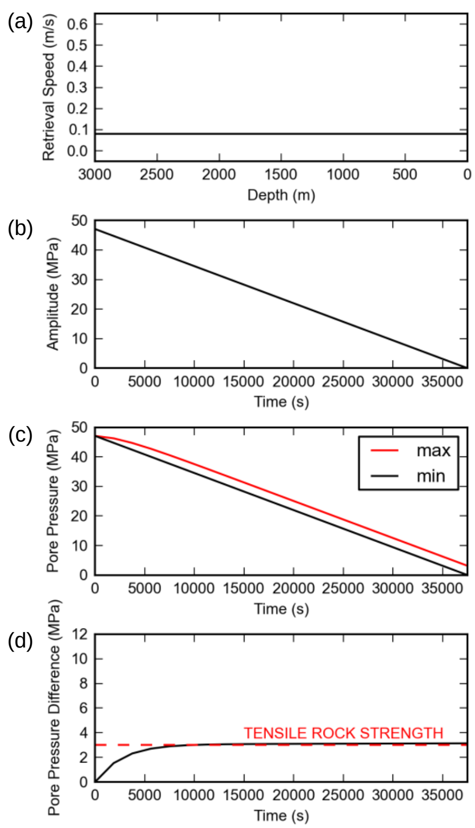

Figure 9. (a) Retrieval schedule and (b) resulting amplitude function. (c) Evolution of maximum and minimum pore pressure. (d) Maximum pore pressure difference within the core sample and tensile rock strength.

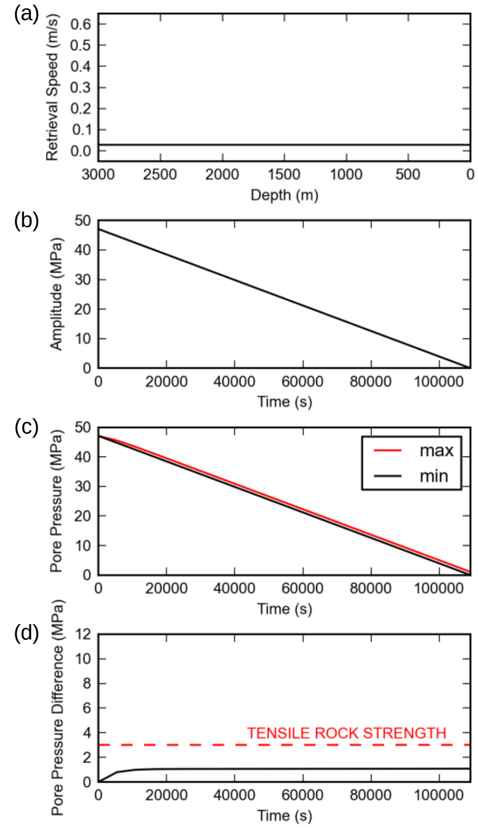

Figure 10. (a) Retrieval schedule and (b) resulting amplitude function. (c) Evolution of maximum and minimum pore pressure. (d) Maximum pore pressure difference within the core sample and tensile rock strength.

3.4 Six Sigma Optimization: shortest retrieval time for which no core damage is predicted for a material parameter range

The retrieval speed associated with a specified probability of success was calculated using the NLPQL optimization technique on the Six Sigma component. Using the aforementioned parameters, for a 90 % probability of success, the total retrieval time is 109137 s (30.3 hours). Figure 10 shows the evolution of pore pressure. The maximum pore pressure difference associated with the retrieval time is 1.1 MPa.

3.5 Variability of permeability and viscosity

The physical key parameter hydraulic conductivity can be computed using permeability and viscosity. Figure 11 shows the influence of variability in each of the parameters as a carpet graph. Dynamic viscosity and permeability span the graph in x- and y-axis, respectively, in the range of considered values, and the maximum pore pressure difference is contoured. The solid black line indicates the maximum pore pressure difference threshold value of 3 MPa, and separates the region in parameter space for which no core damage from decompression is predicted (left of the line) from the region for which core damage from decompression is predicted (right of the line). Core damage from decompression is predicted for relatively low permeability and relatively high viscosity, which is consistent with the notion that both limit the ability of the pore fluid to equilibrate pore pressure differences.

The default values for permeability and viscosity used in the study are denoted by a small black star at the center of the plot. For the purpose of illustration, possible ranges of material parameter uncertainty (20 % in permeability, 5 % in viscosity) are plotted as error bars. The areal extend of the uncertainty range left of the solid black threshold line compared with the total areal extend of the uncertainty range measures the probability of successful core retrieval, i.e., the probability for which no pore pressure damage from decompression is predicted.

3.6 Optimum variable retrieval speed

An optimum core retrieval speed that varies with depth has been obtained by using the modified sim-flow for a piece-wise constant retrieval speed. Figure 12 shows a comparison between the variable optimum retrieval speed and the constant optimum retrieval speed discussed previously. Figure 12 also shows the resulting pore pressure differences. Initially, the variable retrieval speed is significantly larger than the constant speed, which leads to a stronger increase in pore pressure difference. In the next step the speed decreases below the constant value, enabling the pore pressure difference to decrease. In all other steps, the variable speed varies slightly above the constant speed. The average speed of the variable retrieval schedule is larger than the constant speed and generates a time savings of about 2600 s (~ 3/4 hours), which is 6.5 % of the constant optimum time. In the variable case the retrieval speed is automatically adjusted during ascent so that the maximum pore pressure difference remains below the threshold. The maximum pore pressure difference is closer to the threshold in the variable case than in the constant speed case.

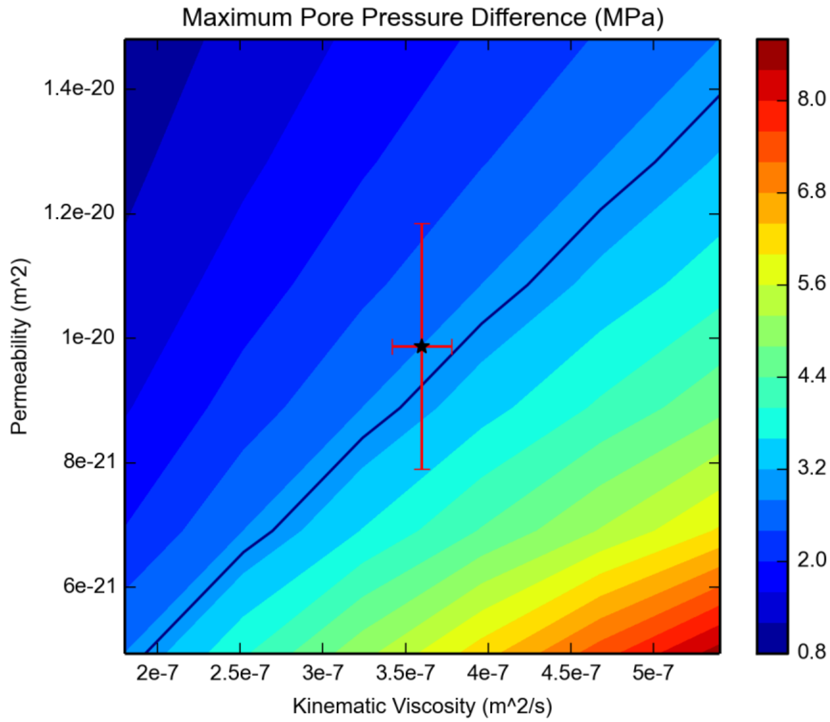

Figure 11. Carpet plot spanned by independent input variables, permeability and kinematic viscosity. The output variable is the maximum pore pressure difference in the core sample. The solid line indicates the threshold, 3 MPa. The star locates the default input values in parameter space. Error bars indicate possible uncertainty ranges.

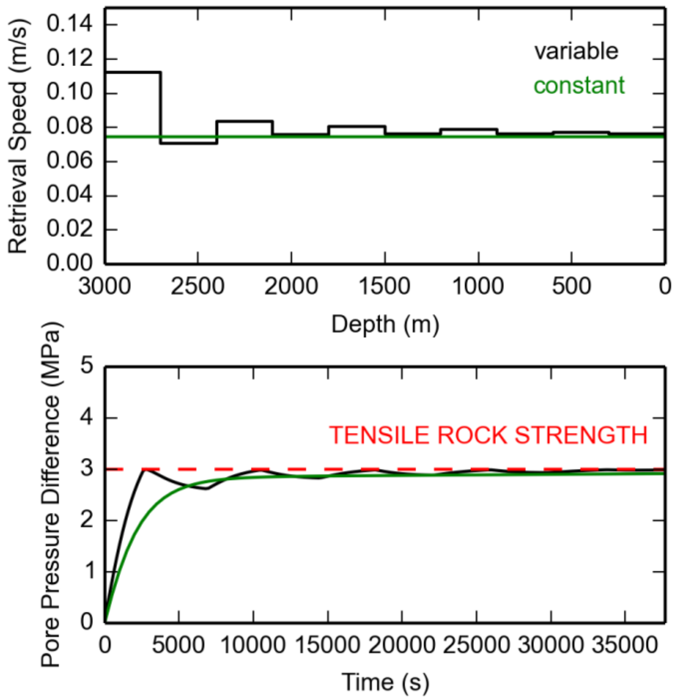

Figure 12. Comparison of optimum retrieval speeds for the constant (green) and the variable (black) model. (a) Retrieval schedule and (b) maximum pore pressure difference within the core sample and tensile rock strength. Each adjustment of the retrieval speed leads to a relative maximum or minimum in the pore pressure difference.

4. Discussion

Figure 13 shows the cases located in design space. The base case and the two revised core retrieval schedules are shown with respect to the design space for which the maximum pore pressure difference constraint is satisfied. The second revision (R2) is near the optimum for the given value of hydraulic conductivity (Opt). The estimated total retrieval times for the second manually revised retrieval schedule R2, 37500 s (10.4 hours), and the optimum speed obtained with optimization technique Opt, 40310 s (11.2 hours), are in good agreement. There is a small discrepancy between the manually selected schedule and the optimum, because the manually selected schedule does not satisfy the decompression damage constraint (the maximum pore pressure in this case is slightly above the threshold value). The total retrieval time for the optimum variable speed case is 37693 s (10.5 hours), which is only 3 minutes longer than the second revision (R2). The major benefit of the optimum variable speed is it enables to closely satisfy the maximum pore pressure difference constraint.

The optimum total time is identified for a scenario where all parameters are precisely known. The probability of success for a case in which hydraulic conductivity forms a distribution spanning about one order of magnitude is only 57.7 %. The probability is relatively low because a significant part of the hydraulic conductivity distribution encompasses lower values than the constant value used beforehand, and a significant part of the distribution falls outside the acceptable design space.

In the constant-parameter case with constant optimum retrieval speed, Opt, the maximum pore pressure difference constraint is satisfied. In scenarios where a parameter varies within a distribution, the probability of success can be raised when a slower retrieval speed is used, because slower retrieval speeds are associated with lower maximum pore pressure differences. The optimum point in design space must be moved away from the constraint boundary so that a sufficient percentage of successful response values can surround the new optimum point. The higher the desired probability of success, the higher the total retrieval time must be. The aforementioned notion is supported by the Six Sigma optimization results: retrieval times of 109137 s (30.3 hours) yield a 90% probability of success. In Figure 13, this optimization case is denoted with p90. At the design point p90 most of the hydraulic conductivity range falls within the region for which the maximum pore pressure difference constraint is satisfied.

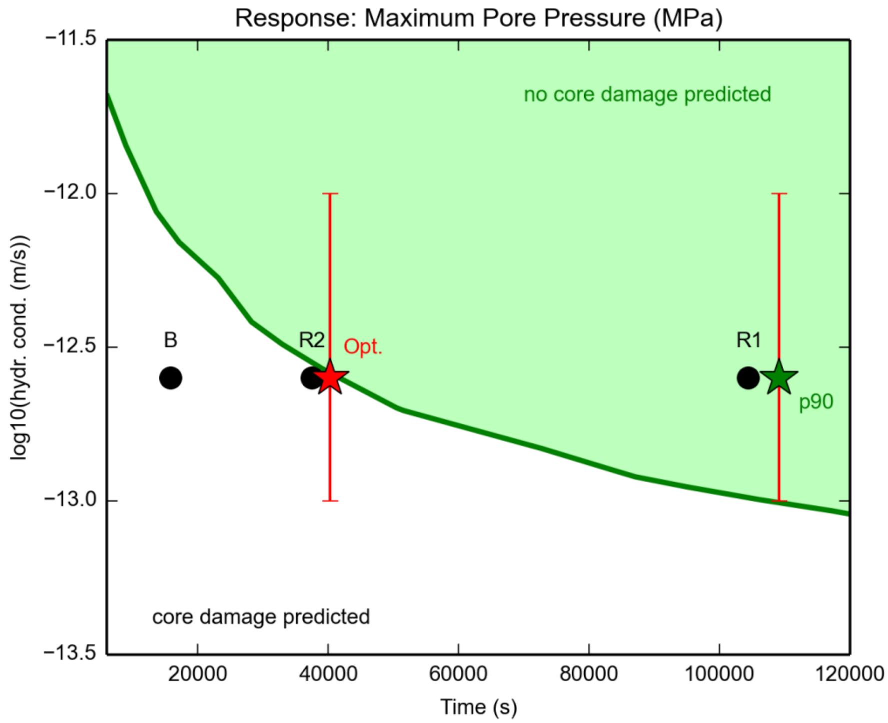

Figure 13. Results located in design space. Shaded in green is the design space for which the constraint is satisfied that maximum pore pressure differences are below the threshold value, which is indicated by the thick green line. B, R1, and R2 denote the manually created retrieval schedules for the base case and the two revisions, respectively. Opt indicates the optimum retrieval speed for the constant parameter case. The label p90 indicates the Six Sigma result with a 90 % probability of success, and the red error bars show the range of distributed values in the key variable hydraulic conductivity.

5. Conclusions

An axisymmetric finite-element model is presented for testing whether core damage from decompression is likely to occur for a given core retrieval schedule. After a small number of iterations an acceptable answer is obtained where the maximum pore pressure difference in the core sample remains close to, or below, the target value given by the tensile rock strength. Optimization techniques such as those implemented in Isight can return the shortest retrieval speed for which decompression is not predicted. Using a modified sim-flow, variable retrieval schedules can be modeled which can result in shorter total retrieval times.

For scenarios in which material parameters are not precisely known, but expected to vary within a distribution, a Six Sigma analysis can estimate the probability of success. Because the constant-parameter optimum is, by definition, near the constraint boundary, it is to be expected that the distributed-parameter case has an unsatisfactory low probability of success at the same design point. The retrieval schedule associated with a 90 % probability of success is predicted using a Six Sigma optimization. Plotting and analyzing results with respect to constraint boundaries in design space is an additional visual verification tool.

In the paper hydraulic conductivity is considered to vary within a given distribution. Hydraulic conductivity is computed from permeability and viscosity, which are two variables typically used in the oil- and gas industry. In practice the uncertainty in viscosity falls within a smaller range than the uncertainty in permeability. It is therefore instructive to plot the influence of various uncertainties in a carpet plot to estimate the probability of success for ranges of uncertainty.

6. References

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