Macro- and micro-FE modelling of wellbore damage due to drilling and coring processes

Modélisation par les éléments finis aux échelles micro et macro de l'endommagement dû au forage et au carrotage

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ABSTRACT: This paper presents the application of the finite element method to evaluate tensile fracturing at different scales in the formation during drilling and coring operations. The first part focuses on evaluating the formation damage process at the macro scale. Both full 3D and axisymmetric macro FE-model are established in order to identify the potential damage mechanisms, to study the size of damage zone as well as to indentify the critical stress changes causing failure cracks at one specific location close to the wellbore tip. In the second part of the paper, the potential mechanisms of damage are investigated in detail at the micro scale (i.e. grain scale) by using a complex 2D micro FE-model reproducing a realistic grain structure taken from the Scanning Electron Microscope (SEM). The stress changes calculated from the macro FE-model are applied at the boundaries of the micro FE-model to simulate the effects from drilling and coring operations. The calculated results show that the 2D micro FE-model is closer to explain the formation damage observed around the wellbore and more pertinent to investigate the physical processes of damage, while it is almost impossible with the macro FE-model.

RÉSUMÉ : Cet article présente l'application de la méthode des éléments finis pour évaluer une rupture en traction à différentes échelles dans une formation rocheuse au cours des opérations de forage et de carottage. La première partie se concentre sur l'évaluation du processus de détérioration de la formation à l'échelle macro. Les deux cas de modélisation 3D et de symétrie axiale par les éléments finis sont mis en place afin d'identifier les mécanismes d'endommagements potentiels et d'étudier la taille de la zone endommagée ainsi que pour identifier les changements de contraintes critiques causant une fissuration. Dans la deuxième partie de l'étude, les mécanismes potentiels d'endommagement sont étudiés en détail à l'échelle micro (*i.e.* échelle de grain) en utilisant un modèle 2D complexe qui reproduit une structure de grain réaliste issue d'observations par microscope électronique à balayage (MEB). Les changements de contraintes calculés à partir de la modélisation macro sont appliqués aux frontières du modèle Eléments Finis à l'échelle micro pour simuler les effets de forage et de carottage. Les résultats calculés montrent que le modèle 2D micro est plus apte à expliquer la détérioration de la formation observée dans le puits de forage et plus pertinent pour étudier les processus physiques d'endommagement qui sont presque impossibles à aborder avec le modèle macro.

KEYWORDS: Multiscale modelling, wellbore damage, finite element

1 INTRODUCTION

Drilling and coring operations disturb and generate stress changes in the rock surrounding the wellbore. These induced stresses, which are quite different in magnitude and sometimes orientation, as compared to the initial conditions, can cause a number of events such as wellbore stability and fracture initiation.

In general, well damage is governed by the in-situ stresses, pore pressure and rock strength. In addition to these dominant parameters, during the drilling and coring operations, wellbore stability may directly or indirectly be affected by the three following effects:

- Stresses from drill bit (shear stresses from torque, lateral stresses due to stress release due to drilling vibration and weight of bit);
- Stresses released due to drilling: difference between mud pressure and the in-situ stresses and reduction by mud-fluid flowing into the formation;
- Stresses released due to temperature reduction due to cooling of the formation rock near the wellbore by the colder mud-fluid.

Recent developments in geophysical logging i.e sonic scanner logging tool together with the Diapole Shear Radial Profiling algorithm have given new insight into the evaluation of 3D field of stresses and material properties around the wellbore (Sayers et. al, 2009). The information from such logs along the well are crucial with respect to predicting potential geomechanical challenges during drilling and coring operations. It was found that one possible mechanism of wellbore damage is tensile failure of the formation during effective stress unloading caused by radial stress release, pore pressure increase by mud-fluid flowing into the formation close to the wellbore tip as well as temperation reduction.

The paper focuses on applying the finite element method to evaluate tensile fracturing at different scales (multiscale) in the

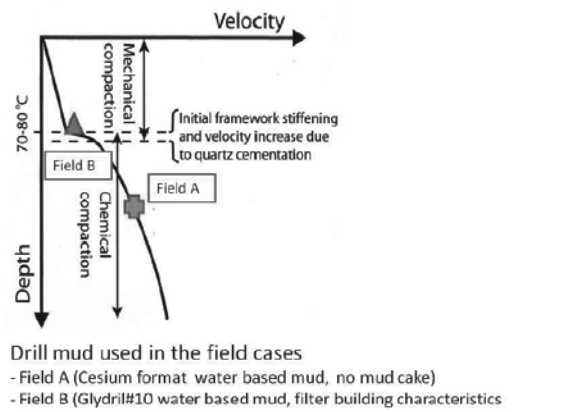

Figure 1. Field data used for study of formation damage. Depth of burial varies between two fields A and B, leading to pronounce difference in terms of quartz cementation. Also use of different muds leads to different mud cakes at wellbore walls.

Table 1. Material properties at wellbore at Field A and B.

Parameters	Field A	Field B	Unit
Depth	~4100	~2400	mTVD
Porosity	16-25	27-32	%
Young modulus	13	5	GPa
Poisson's ratio	0.15	0.27	-
Cohesion	8.7	3.2	MPa
Friction angle	33	29.1	degree
Tensile strength	3.2	1.2	MPa

formation during drilling and coring operations. In the first part, an example of workflow will be outlined throughout the numerical modelling performed at two macro (continuum) and micro scales based on data from the two field cases: Field A and B. Figure 1 illustrates the locations of Field A and B where the Radial Diapole Profiling data is available. The material properties at the two field cases are given in Table 1. They basically differ from each other in term of burial depth, leading to different degrees of cementation between grains.

The second part will present the FE-results calculated by using the macro FE-model while the third part will discuss in detail about the application of the 2D micro FE-model for analysing and predicting tensile fracturing observed on a micro level (grain scale) in the formation during drilling and coring operations.

2 METHODOLOGY AND WORKFLOW

In the first stage a macro 3D FE-model was established for calculation of continuum stress changes around wellbore, which were mainly caused by lateral vibrations and torque from drill bit, radial stress release and mud-fluid flowing into the formation and temperature changes as illustrated in Figure 2. Several assumptions have been made:

- The rocks behave as a homogeneous material. Hence, its mechanical behaviour can be described by using a continuum mechanical approach;
- The distances from the wellbore to the boundaries in the two horizontal (x) and (z) and vertical (y) directions were sufficiently large to avoid any effect of the outer boundaries on the stress changes close to the wellbore;
- The elements were modelled assuming an elastic perfectly plastic, frictional-cohesive material that followed the Mohr-Coulomb failure criterion after the onset of yield. In addition to shear failure, the model also performs failure in tension. The material parameters used in the Mohr-Coulomb model are summarised in Table 1.

This FE-model was applied for the detailed study of the two Field cases A and B presented in Figure 1. A transient pore pressure analysis was performed in order to study the time dependent dissipation of excess pore pressure due to the mud-fluid flowing into the formation. In general, a total of five numerical simulation steps need to be performed in order to evaluate the stress changes in the rock surrounding the wellbore during drilling and coring operations:

a. Initial stresses are first generated by applying the in-situ stresses to the FE-model without the wellbore. The considered stress states correspond to 2400 m "true vertical depth" (TVD) and 4100 m TVD below mean sea level for Field B and Field A, respectively;
b. The wellbore is then excavated under the hydraulic support from the net mud pressure to simulate the drilling stage;
c. In this step, forces at the drill bit are applied. All forces from cutters, bit body and gauge pads are summed and applied as resulting forces at the centre of the drill bit;
d. Then the mud-fluid infiltrates into the formation and gives an applied increase of pore pressure around the wellbore;
e. Finally, the reduction of the temperature is simulated by reducing the volumetric strain.

From a parametric study the mud temperature was found to be important with respect to generation of tensile fractures which are the most plausible failure mechanism. Downhole temperature logs measured at the drill bit were available, but these did not cover the entire history of temperatures during the various stages of drilling and circulations in the period between drilling and logging of the actual intervals. Due to the large impact of temperature on failure and the poorly documented temperature history of the study intervals, an assumed constant temperature change is applied one wellbore radius into the formation in order to simulate the cooling of formation during process of drilling. The stress situation one radius into the formation was evaluated with respect to fracturing due to tensile failure.

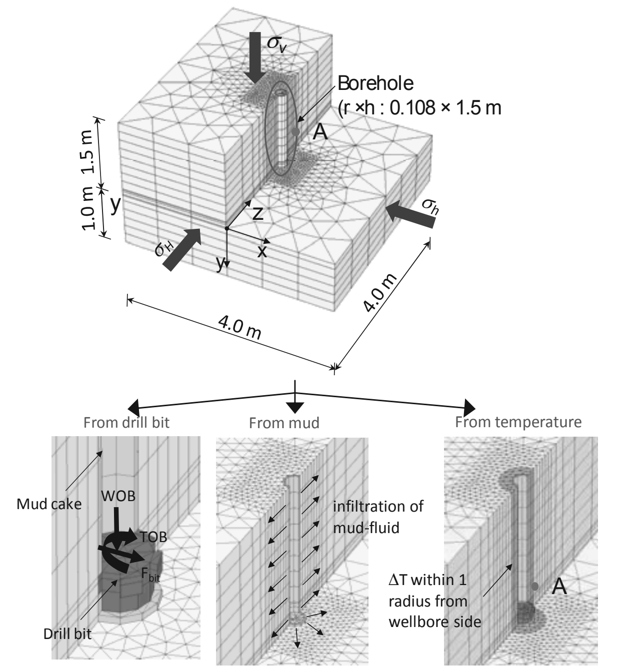

Figure 2. Full 3D FE modelling of different loads due to drill bit torque and axial load, mud-flow into formation and temperature change within one radius from wellbore wall.

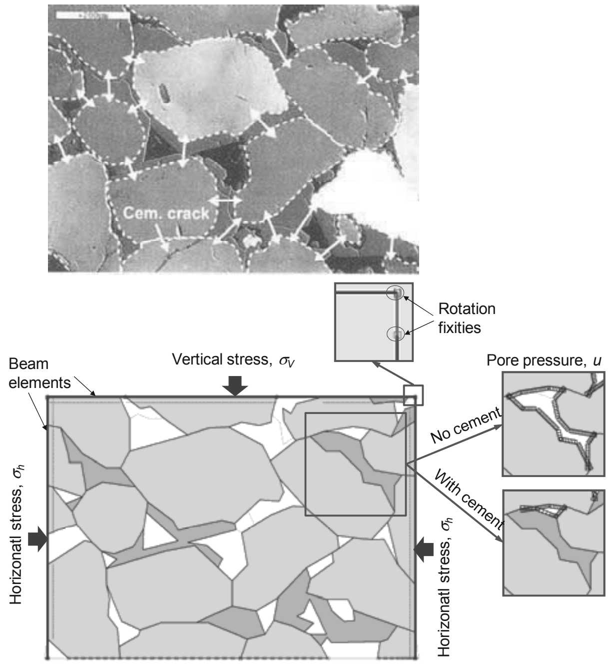

Figure 3. Cathodoluminescence SEM picture (top) from Storvoll (2004) and equivalent 2D micro FE-model (bottom) used for studying formation damage around wellbore during drilling and coring operations.

Then in the second stage the stress changes obtained from the macro FE-model are applied at the boundary of a micro FE-model in order to investigate tensile fracturing on the micro level. Figure 3 shows the FE-model established based on a high resolution cathololuminescence SEM picture of well cemented sandstone (from Storvoll, 2004), where authigenic quartz cement can clearly be separated from the original grains. For the deeply buried Field A which has undergone both mechanical and chemical compaction the cemented areas were activated at a stress condition corresponding to a burial depth of about 4.1 km corresponding to depth for onset of quarts cementation at temperatures of 70 - 80^{0}C (Bjørlykke, 1989). Field B has undergone purely mechanical compaction due to the shallow burial depth (< 2.4 km), and no cement was applied for this model.

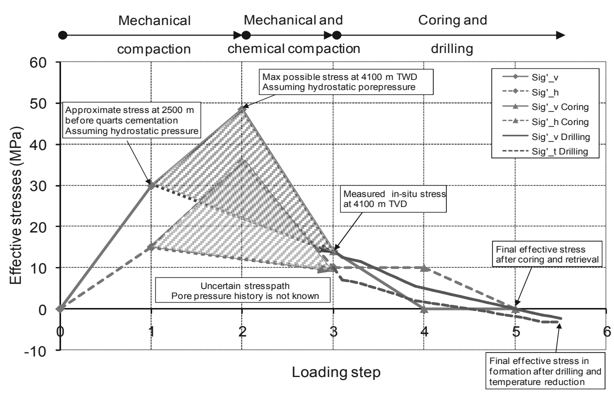

Figure 4. Idealized stress paths for Field A. Stress changes during drilling and coring process are based on "macro" stresses released at material point A plotted in Figure 5.

Table 2. Simplified burial history applied in micro FE-model.

Step	Description	σ_V (MPa)	σ_h (MPa)	u (MPa)
1	At 2500 m, no cement	55	40	25
2	At 4100 m, with cement	90	77	41
3	At 4100 m, in-situ state	90	85.8	75.8
4	Mud pressure & mud-flow	88.4	82.8	82.2
5	Temperature reduction (^{0}C)			
-	2.4	87.9	82.4	82.2
-	9.5	86.4	81.4	82.2
-	19.1	84.4	80.0	82.2
-	33.3	82.2	81.4	82.2
-	57.1	76.3	74.4	82.2
-	66.7	74.4	72.7	82.2
-	71.4	73.5	72.6	82.2

σ_V, σ_h are total vertical and horizontal stresses, respectively
u is pore pressure

Figure 4 shows an idealized loading path being applied to the micro FE-model at Field A. The stress changes during drilling and coring processes are based on the "macro" stresses released at the material Point A located at a distance of one radius into the formation from the wellbore wall and two radius up from the wellbore tip (see Figure 5). In the process of coring there is first a total vertical stress unloading. This corresponds to removing the weight of overburden during coring. Finally, the horizontal stress is completely unloaded. This corresponds to a situation after coring and core retrieval when pushing out the core from the core cylinder. In the formation adjacent to the wellbore the stress change is a combination of effect of pore pressure changes, temperature effects and stresses from the process of drilling. This is a complex process that requires FE modelling. Therefore the final load step has been directly taken from the calculated results of the macro FE-model. The effective vertical and effective radial stresses at Point A after drilling are shown in Figure 4. This includes unloading due to mudflow into the formation and cooling of the formation. Note that the final effective stresses shown in the figure corresponds to a cooling of about 70^{0}C, which is a higher temperature reduction than experienced in the field. Also, the tangential stress which is most critical with respect to micro fractures is not shown in this figure. Table 2 summarizes the burial history at Field A which is applied at the boundary of a micro FE-model in order to investigate tensile fracturing on the micro level.

3 RESULTS FROM MACRO FE-MODEL

From the results of the 3D modelling in it is found that at a distance of one radius from the wellbore wall the application of the drill bit forces gives minor effect in terms of stress changes compared to the effects from mud pressure, mud-fluid flowing into the formation and temperature reduction. In fact, damage only occurs very locally at the edges of the gauge pads and drilling cutters. Since the effects from the drill bit can be neglected, for a matter of modelling simplification and also to minimize the time necessary for processing, a macro axisymmetric FE-model has been established and used for studying the other effects with respect to the wellbore damage.

Figure 5 shows that the macro (continuum) analysis predicts tensile fracturing within one radius into the formation (point A) after circa 67^{0}C of cooling. This value is not in agreement with field observations which indicate fracturing at much lower temperature differences as observed from the Radial Dipole Profiling data. Hence a further evaluation of tensile fracturing on a micro level was performed with a 2D micro FE-model (grain scale).

4 RESULTS FROM MICRO FE-MODEL

In both the Field A and the Field B case, it is found that onset and development of tensile fractures starts at a lower temperature reduction in the micro FE-model (Figure 6) then in the macro FE-model (see Figure 5). The micro FE-model thus seems to pick up formation damage that cannot be found when applying a macro FE-model, and this model is closer to explain the observed potential stiffness reduction based on the difference between the mud temperature and the formation temperature of 25-35^{0}C as indicated from downhole temperature log. There are however limitations in the 2D micro model and the results should only be used as a indications of that failure mechanisms may occur at earlier temperature stages than what is obtained by the classical macro (continuum) model.

One physical explanation for this earlier development of tensile failure in the micro model compared to the macro model is partly linked to the stress history prior to coring or drilling. For cemented sandstone (i.e. Field A) the submerged weight of the overburden is initially carried by the original grain framework. When introducing cement to grain boundaries in the pore space during chemical compaction, the cement will initially be more or less stress free since the overburden pressure is already carried by the original grain framework. During unloading, since the stresses are smaller in the cement, it will therefore first reach tensile failure. Also, the micro model experience local stress concentrations which are not a part of the global continuum model. Temperature changes affect this local stress pattern differently compared to global unloading. This might explain the higher amount of tensile failures in the micro model also for the un-cemented Field B case. Further understanding of these physical processes is important to be able to explain and quantify core damage and formation damage in general.

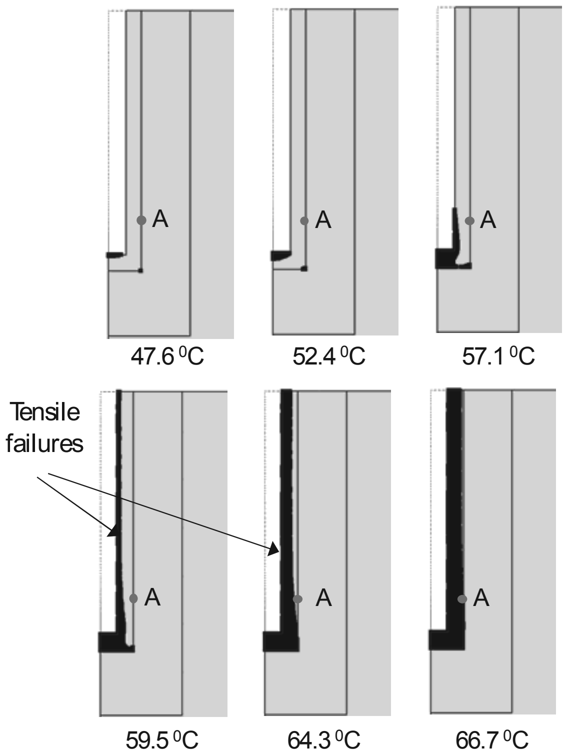

Figure 5. Development of tensile failures in formation predicted by macro FE-model.

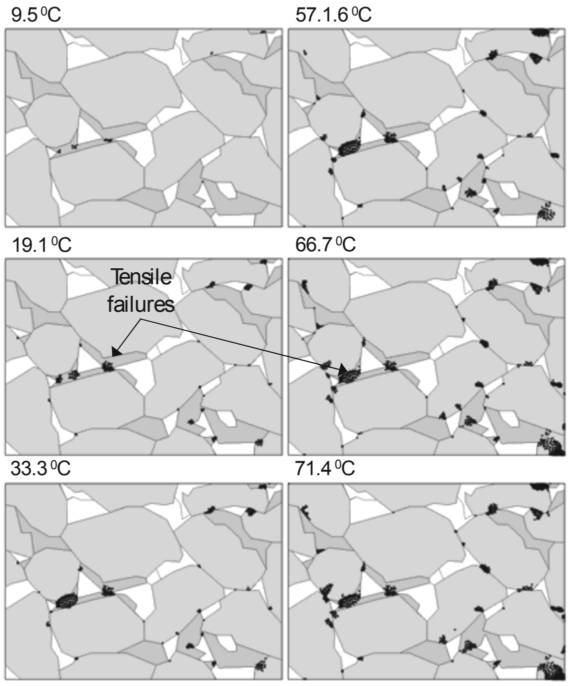

Figure 6. Development of tensile failures in formation predicted by micro FE-model.

5 CONCLUSIONS

The paper presents an approach for modelling the process of core and formation damages during drilling. Numerical simulations show that fracturing on a local micro scale seems to start at an earlier stage compared to macroscopic failure at the macro continuum scale. The main hypothesis or physical explanation for this earlier fracturing in the micro model compared to the macro model is partly linked to the stress and cementation history of sediments prior to coring or drilling, in interaction with mechanical, thermal and flow stresses induced during drilling, coring and production. This work is a promising contribution to a better understanding of physical processes resulting in core damage and formation damage in general. However, the work was limited to 2D micro modelling.

Ideally, due to variability in possible grain structures and material properties and the 2D idealization of the 3D problem, the micro model should be extended to 3D and calibrated with laboratory data. There are also major uncertainties related to temperature history within the well and temperature distribution from the well into the formation. Further, available experimental data on the stress dependent anisotropy of sandstones shows very complex interrelationship between stress magnitudes and directions, and shear modulus. Future activities should also address better constitutive models for stress induced anisotropy in uncemented and cemented materials.

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