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Progressive rock deformation and rock-casing contact around borehole in Bingham viscoplastic rock

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1 INTRODUCTION

Time dependent closure of underground opening has been observed for decades in tunnel and mining engineering. Recently in petroleum industry, this phenomenon has also attracted attention when progressive closure was detected in boreholes drilled in shale rock formations (Williams et al. 2009). Borehole closure can be a critical problem in drilling operations, but it does not always have adverse effects. In fact, by sealing the casing annulus, it can potentially establish a hydraulic barrier, prevent fluid leakage, and thereby provide an alternative solution to conventional plug and abandonment operation.

Williams et al. (2009) discussed the mechanism of progressive borehole closure and its association with the shear failure of the rock. Works by Fjær et al. (2018) have shown that a drawdown of casing annulus pressure can trigger progressive borehole closure. Also, laboratory studies have identified the existence of rock damage around the borehole using post-test µCT scan. The combined field observation and lab test suggest that the progressive borehole closure can be attributed to a time-dependent rock yielding process. In the scope of rheological constitutive model, we choose Bingham viscoplastic constitutive model, implemented in *FLAC* (Itasca 2016) as a user-defined model (UDM). The diffusion of pore pressure is also involved. The success of *FLAC* simulation with user-defined model has been proven many times (see works by Boidy et al. 2002, Bonini et al. 2007, Barla et al. 2011, Liu et al. 2015, Souley et al. 2017).

The objective of this work is to simulate progressive borehole closure in field conditions both before and after rock-casing contact, especially to predict whether a hydraulic barrier can be formed in casing annulus.

2 PROBLEM DEFINITION AND CONSTITUTIVE MODEL

The assumption is that of an isotropic and homogeneous rock subjected to isotropic or anisotropic in-situ stress state $\sigma_h < \sigma_v < \sigma_H$, where σ_h, σ_v, and σ_H denote minimum horizontal, vertical, and maximum horizontal stress. The porous rock is fully saturated with brine at in-situ pore pressure p_0. A vertical cylindrical wellbore with radius r_w is drilled through the rock, then a casing with outer radius $r_c < r_w$ is inserted coaxially. The casing annulus is defined as the space between the borehole and the casing, which is filled with brine. The width of the casing annulus is defined as $w = r_w - r_c$. The problem is two-dimensional, and plane strain conditions apply. The surface pressure of the casing annulus valve, and the hydraulic pressure provide the casing annulus pressure p_c at the target formation depth (frictional forces are neglected). The borehole wall is assumed to be permeable, p_c is the pressure applied on both rock frame and pore fluid at r_w. See geometry, initial and boundary conditions in Figure 1.

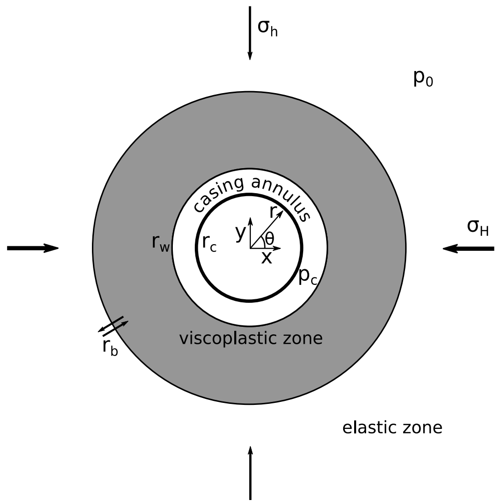

Figure 1. Borehole geometry, stress conditions, viscoplastic and elastic regions around the borehole.

Borehole closure is stimulated by an instantaneous stress change from in-situ (total) radial stress to casing annulus pressure p_c at the rock boundary $r = r_w$. p_c is assumed to be small enough to trigger rock failure and produce a viscoplastic zone around the borehole. The radius of the viscoplastic region r_b can expand or shrink depending on the stress condition at the borehole wall and whether contact is formed or not with a casing.

The sudden stress change at the borehole wall induces a stress concentration around the borehole. The stress state corresponding to this short-term response can violate a given Mohr-Coulomb yield criterion. In the framework of the Bingham constitutive law, viscous stresses are developed to bring the over-stress back to the yield envelope asymptotically in time. The viscous strain rates obey a flow rule: the magnitude is proportional to the deviatoric over-stress invariant on the π-plane and is inversely proportional to the rock viscosity.

The yield criterion used in the simulation has the following features:

- Intact and residual yield functions based on Mohr-Coulomb criterion to govern viscoplastic shear failure. Rock first yields when the stress state (overstress) violates the intact yield criterion while the residual criterion governs the time-dependent yielding process activated by rock viscosity.
- Tensile strength governs plastic tensile yielding.
- Softening or hardening behavior of constitutive parameters is considered in terms of viscoplastic strain for shear failure and plastic strain for tensile failure.
- Non-associated flow potential.

The above viscoplastic constitutive model is introduced in *FLAC* via a User Defined Model (UDM) coded in *FISH*, and *FLAC* handles the rest of the logic automatically, including geometry and pore pressure diffusion.

3 RESULTS AND DISCUSSION

A field case study in the North Sea is used to analyze the behavior of borehole closure in shale before and after rock-casing contact. In both cases, the borehole closure is induced by the drawdown of casing annulus pressure. An elastic material is used to represent the casing behavior. The simulation is conducted in large strain, and an interface between casing and rock is used to allow automatic contact detection as the rock deforms into the casing annulus. The input properties and conditions for the simulations are provided in Table 1. The properties of cohesion, friction, dilation and viscosity can experience softening, the user-defined softening correlations are given in Table 2.

Table 1. In-situ conditions and constitutive parameters.

Inputs	Value	Unit
Young's modulus of the rock frame	0.80	GPa
Poisson's ratio of rock frame	0.30	-
Friction angle (intact)	15.03	º
Dilation angle (intact)	11.54	º
Cohesion (intact)	1.53	MPa
Tensile strength (intact)	1.00	MPa
Rock viscosity (intact)	10	GPa·s
Porosity	0.15	-
Permeability	0.022	mD
Water density	1000	kg/m^2
Water bulk modulus	2.25	GPa
In-situ stress, maximum horizontal	32	MPa
In-situ stress, minimum horizontal	28	MPa
In-situ stress, vertical	30	MPa
In-situ pore pressure	18	MPa
Casing annulus pressure	15	MPa
Biot coefficient	1	-
Borehole radius	15.56	cm
Outer radius of casing	12.54	cm
Gap of casing annulus	3.02	cm

Table 2. Correlation of softening behavior.

Shear viscoplastic strain	Cohesion	Friction	Dilation	Viscosity
-	MPa	∘	∘	GPa·s
0	1.53	15.03	11.54	10
$1 \cdot 10^{-10}$	1.40	13.00	10.00	10
0.1	1.00	9.00	6.00	5
> 0.1	1.00	9.00	6.00	5

Tensile plastic strain	Cutoff
-	MPa
0	1.00
$1 \cdot 10^{-10}$	1.00
0.1	0.50
> 0.1	0.50

The in-situ stress is anisotropic. The simulations predict the time-dependent borehole closure shown, at three different times, in Figure 2. When the pressure drawdown is applied at the borehole wall, more shear stress concentrates along the direction of the minimum horizontal stress (y-direction). In the later progressive borehole closure, additional yielding and borehole closure are triggered along this direction, and the rock-casing contact first occur in this direction. At the end of the simulation, the displacement field reaches an asymptotic state. However, the displacement in the x-direction is not large enough to close the casing annulus. A hydraulic barrier fails to be established in this case. We also observe (figure is not shown here) that after the first contact along y-direction, the rate of borehole displacement along other angular directions decreases. A physical explanation can be that after the first contact along y-direction, the recovery of contact pressure triggers a *decrease* in shear stress concentration (as opposed to an *increase* in shear stress concentration, triggered by the pressure drawdown at the borehole wall). Noting that the shear stress concentration yields the over state of shear stress around the borehole, this opposite effect will inversely decrease the overstress and hence delay the viscoplastic failure.

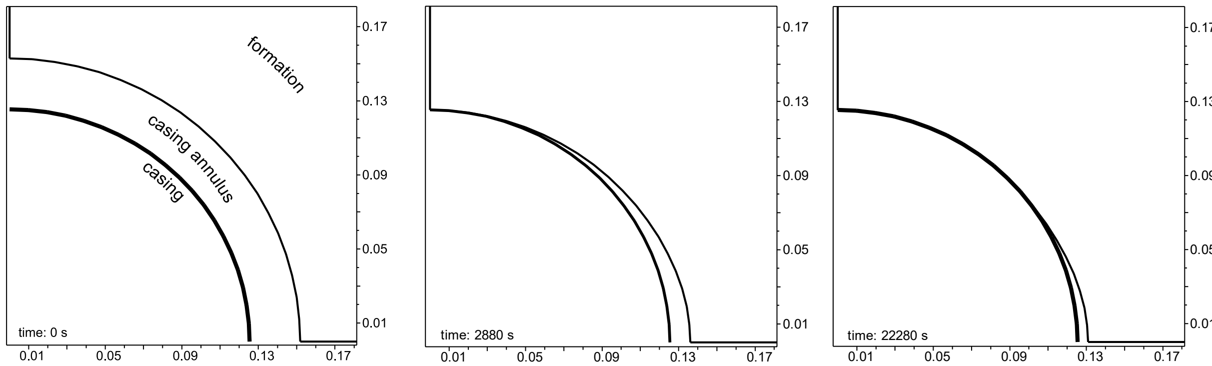

Figure 2. Borehole closure under anisotropic in-situ stress.

4 CONCLUSIONS

The purpose of the work is to study the time-dependent rock yielding and borehole closure in viscoplastic rock, such as shale or mudstone, and to identify whether natural closing of the casing annulus can occur. Specifically, we use *FLAC* numerical simulations to study the viscoplastic rock yielding triggered by a sudden drawdown of casing annulus pressure and the corresponding borehole closure before and after the rock-casing contact. The simulations show that the drawdown of casing annulus pressure indeed can trigger the viscoplastic yielding and borehole closure in certain conditions. The simulation with anisotropic in-situ stress shows that, the casing annulus closes in the direction of the minimum horizontal in-situ stress, while it remains open in the direction of the maximum horizontal stress. Overall, the drawdown of casing annulus pressure is an effective means to stimulate borehole closure, however the establishment of a hydraulic barrier depends on specific conditions (including in-situ stress values). More analyses will be performed to identify the factors impacting the recovery of contact pressure. Also, the viscoplastic model results are currently being compared with the experimental results; this will help improve the constitutive model prediction capabilities and characterize the constitutive model parameters.

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