Study on Borehole Stability of Shale Gas Well under Multi-field Coupling

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Abstract

The mechanical response of mud shale under the action of multiple field coupling is always a hot topic in the field of drilling engineering. In this paper, a multi-field coupled model is established, using the solid mechanics module embedded in COMSOL and combined with the General form in PDE module to complete the setting of the model. The grid encryption function is used to encrypt the area around the well, which makes the calculation results more advanced and more in line with the actual situation on site. The results show that the collapse process of rock around the shaft wall is a dynamic evolution process involving space and time, and COMSOL can well simulate the above 4-D process. The simulation results can be used to analyze and simulate the effect of time dependence on wellbore stability during drilling. It can also help drilling engineers design drilling plans (including design and calculation of mud safety density window, mud salinity, etc.).

Introduction

The success of the shale gas revolution launched by the United States in 2015 transformed the us from an oil and gas importer into an oil and gas exporter. This makes shale gas a hot topic in the energy field. Shale gas is cleaner and richer than coal and oil. Two key technologies used for developing shale gas are horizontal well drilling technology and fracturing and reforming formation technology. However, as shale has stronger chemical activity than other strata, it is very easy for the shaft wall to collapse and become unstable in the process of drilling through the reservoir. The use of oil-based slurry can overcome the above problems, but it is expensive and environmentally limited.

The popularity of water-based mud depends on a deep understanding of shale hydration. In the process of shale hydration reaction, temperature field, ion

concentration field, seepage field and stress field all exert mechanical effects on the rocks around the shaft wall to different degrees, and there are mutual coupling effects among the three, which change continuously with time. The dynamic response of shale under the action of multiple field coupling is always a hot topic in the field of drilling engineering. At the same time, it is also the theoretical basis to maintain the well wall stability during the water-base mud drilling.

1. Coupling process

The effects of themo-poro- chemical elastoplasticity on stresses around wellbore drilled in low permeable chemically active shale are investigated. An *initial stress* method is used to solve the non-linearity of plasticity equation. It is well known that the *initial stress* method has a great computational advantage over other methods such as the tangential stiffness method or successive approximations. Further, the *initial stress* method allows the non-linear plastic equation to converge unconditionally (Zienkiewicz and Taylor 2000b)In this work, first the governing equations of thermo-chemo-poroelasticity are introduced and then elastoplastic constitutive law is presented.

2. Coupling model

Navier equations for displacements: A momentum balance equation is employed to derive the Naviertype equation for displacements as:

$$(K+\frac{G}{3})\nabla(\nabla u)+G\nabla^2 u-\alpha\nabla p+\omega_0\chi a\nabla C^S-\gamma_1\nabla T=0 \qquad (1)$$

where K and G are bulk and shear moduli, u is the rock displacement and T is the temperature of the porous medium.

Pressure diffusion equation: Using conservation of mass for a weakly compressible fluid along with the expression for the flux gives a coupled fluid diffusion equation as:

$$\frac{\alpha\partial\varepsilon_{ii}}{\partial t}+(Q+B)\frac{\partial p}{\partial t}+\beta\chi\frac{\partial C^S}{\partial t}-\gamma_2\frac{\partial T}{\partial t}=\frac{k}{\mu}\nabla^2 p-\frac{k\Re\rho_f aRT}{\mu cM^S}\nabla^2 C^S-K^T\nabla T \qquad (2)$$

where α is the Biot's Coefficient, p is pore pressure, k is permeability, μ is the fluid viscosity. ε_{ii} and C^S are the components of total strain tensors and solute mass fractions. Also, $\Re$ is the standard solute reflection coefficient (or membrane efficiency), R is the universal gas constant and M^S is the molar mass of the solute. K^T is the thermal osmosis coefficient.

Equation for solute diffusion: Conservation of a solute mass in rock yields the following equation for solute transfer:

$$\phi\frac{\partial C^S}{\partial t} - D\nabla^2 C^S - C^S D^T \nabla^2 T = 0 \qquad (3)$$

Where D is the solute diffusion coefficient and D^T is the coefficient of thermal diffusion.

Equation for thermal conduction: Conservation of energy balance in the rock yields the following equation for thermal conduction:

$$\frac{\partial T}{\partial t} - c^T \nabla^2 T = 0 \qquad (4)$$

where c^T is thermal diffusivity.

The coefficients in the governing equations are:

$$\chi = (1-\frac{C^S_{mean}}{cRT\rho_f}) \ , c = C^D_{mean} \ , a = \frac{1}{C^S_{mean}} \ , \alpha^{'} = (\alpha - \frac{M^S\omega_0}{cRT\rho_f}) \ , \beta = \frac{\omega_0(\alpha-1)}{K}$$

$$B^{'} = \frac{\omega_0(\alpha-1)}{K}\frac{M^S}{cRT\rho_f}, Q^{'} = (Q + \frac{\phi}{K_f}) \ , Q = \frac{(\alpha-\phi)}{K_S}$$

$$\gamma_1 = K\alpha_m + \frac{s_0\omega_0 M^S}{RTC^D_{mean}} \ , \gamma_2 = \alpha\alpha_m + (\alpha_f - \alpha_m)\phi + \frac{s_0\omega_0(\alpha-1)M^S}{KRTC^D_{mean}}$$

where C^D_{mean}, C^S_{mean} are the average initial mass fraction of diluent and solute in a shale formation, respectively. K_f, K_S, ϕ and ρ_f are fluid bulk modulus, solid bulk modulus, porosity and fluid density, respectively. Also, α_m and α_f are the thermal expansion coefficient of solid and fluid,respectively, and s_0 is the reference value of the specific fluid entropy at the average system temperature. The chemo-mechanical

parameter ω can be defined as follows:

$$\omega^S = \omega^D = \omega_0 \frac{M^S}{RT}$$

3. Basic parameters and boundary conditions

Rock mechanical parameters	
Drained Poisson's ratio	0.219
Undrained Poisson's ratio	0.416
Skempton coefficient	0.915
Bulk Young's modulus	4.4GPa
Maximum horizontal stress	23MPa
Minimum horizontal stress	20MPa
Solid bulk modulus	77.5GPa
Hydraulic parameters	
Drilling fluid pressure	26MPa
Initial reservoir pressure	21MPa
Fluid bulk modulus	2.5GPa
Chemical parameters	
Average solute mass fraction in formation	0.1
Average solute mass fraction in drilling fluid	0.2
Molar mass of solute	0.0585Kg/mol
Solute diffusion coefficient	5e-9㎡/s
Membrane efficiency or reflection coefficient	0.1
Othe parameters	
Formation temperature	353.15K
Drilling fluid temperature	333.15K
Wellbore radius	0.1m
Fluid viscosity	3e-4Ps·S
Fluid density	1211.21Kg/m³
Porosity	0.218

It is assumed that compressive stress is positive and tensile stress is negative. The rock is considered as a homogenous porous medium. The plane strain hypothesis and instantaneous drilling are used to solve the non-linear system of equations. Solving the non-linear system of equations requires knowledge of the initial solute concentration, temperature and pore pressure within the flow domain:

$C^S(x,y,t) = C^S_{Mean}(x,y)$ for t=0

$P(x,y,t) = P_i(x,y)$ for t=0

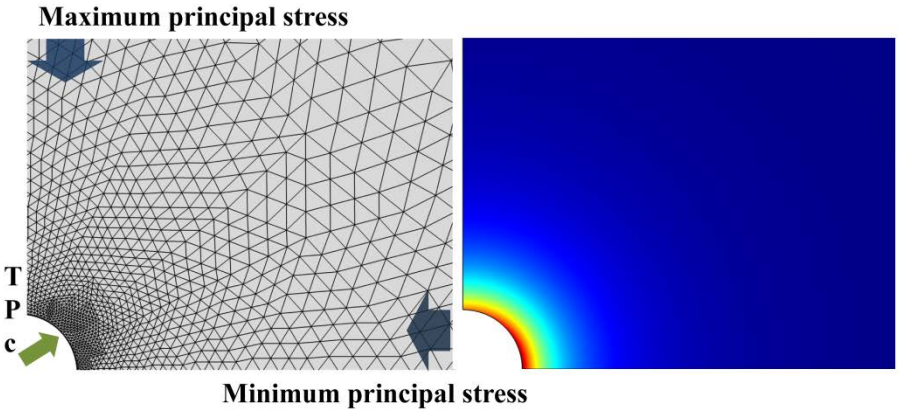
$T(x,y,t) = T_i(x,y)$ for t=0

A Dirichlet type boundary condition is applied to the inner boundary for the solute concentration, temperature and pore pressure as follows:

$C^S(x,y,t) = C_1^S(x,y,t)$ on boundary

$P(x,y,t) = P_1(x,y,t)$ on boundary

$T(x,y,t) = T_1(x,y,t)$ on boundary



4. Results and discussion

Since shale is an ultra-low permeable pore medium, the effect of heat convection is ignored in the energy conservation equation (4.2.15).We compared the results with the analytical solutions (Ghassemi and Zhang,2004).Our results are clearly consistent with the analytical solution.

Figure.1 shows the typical transient temperature distribution of heat conduction.This indicates that the formation is gradually cooled by drilling fluid injected from the surface.

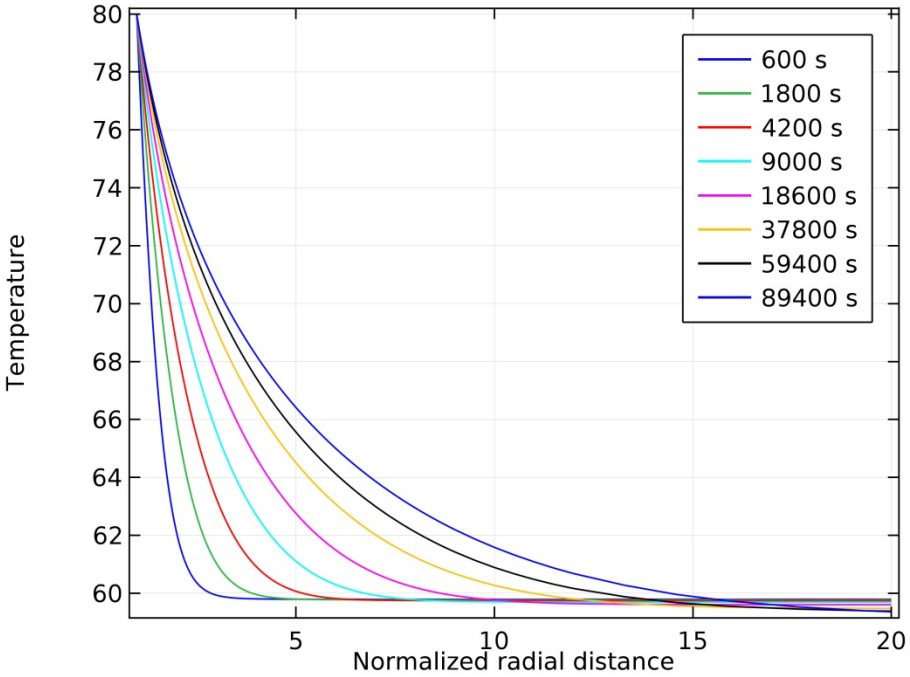


Figure 1

Figure.2 shows the pressure distribution near the well with time.Is the classical pressure wave transfer curve.With the time of drilling and opening the hole, the pressure wave front gradually moves along the hole radial direction from the hole wall.Meanwhile, as can be seen from the figure, its size gradually decreases.This phenomenon is caused by energy dissipation.

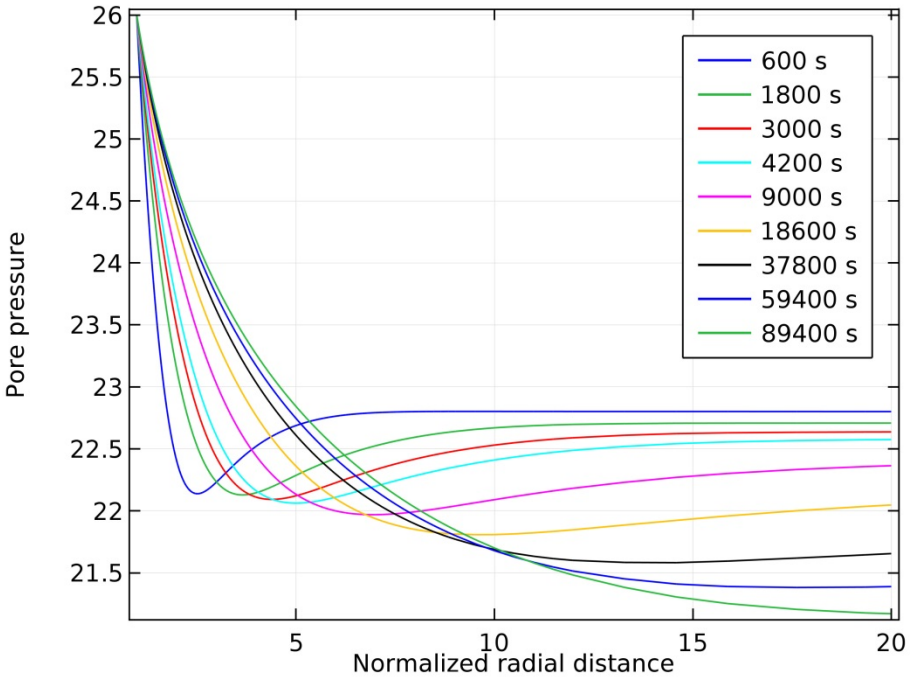


Figure 2

Figure.3 shows the distribution of radial stress around shale gas Wells over

time.From the solution results, the stress peak is not in the hole wall out, but in the formation with a certain distance from the hole wall.This is quite consistent with reality.In actual drilling, there are large collapse slabs in the mud returned from the top, which fully shows that the fracture point of mud shale section is at a certain distance from the well wall.This result is consistent with Ghassmi's paper results.

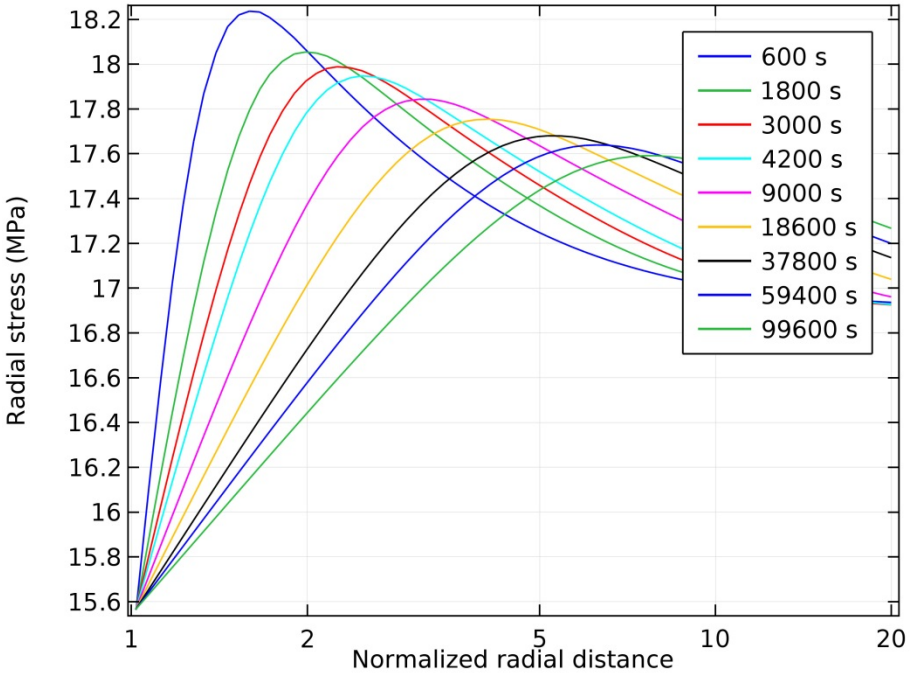


Figure 3

Figure.4 shows the spatial and temporal distribution of the solute of the drilling fluid around the well.As the salinity of the drilling fluid is higher than that of the formation, solutes in the solution gradually spread to the formation and finally reach stability.

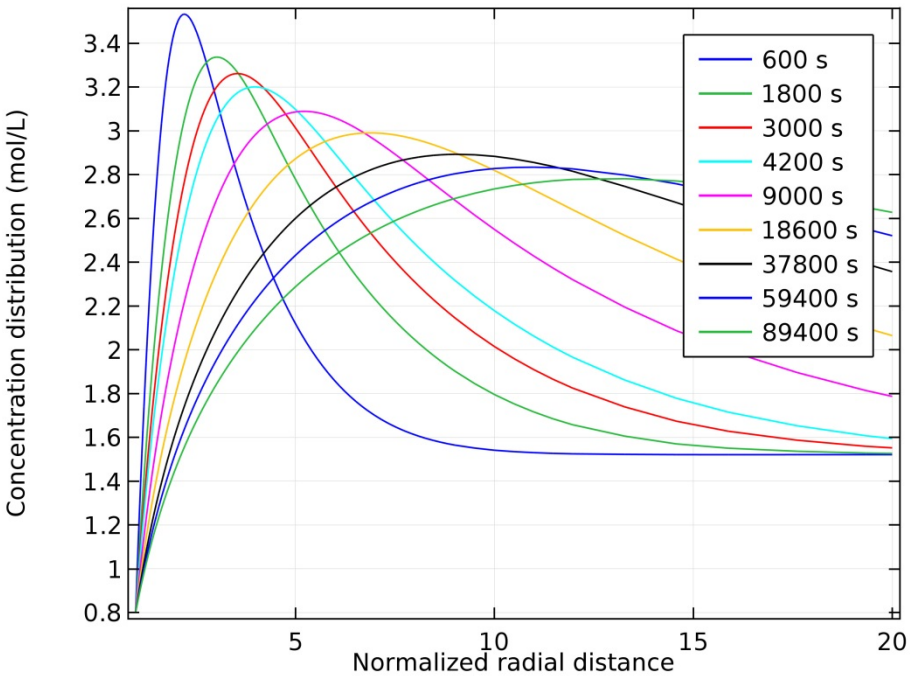


Figure 4

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