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Comprehensive stability analysis of an inclined wellbore embedded in Colorado shale formation for thermal recovery

Biao Li[a,*], Ron C.K. Wong[b], Bin Xu[a,c], Baohong Yang[a,c]

[a] Department of Building, Civil & Environmental Engineering, Concordia University, Montreal, Quebec, Canada H3G 1M8
[b] Department of Civil Engineering, Schulich School of Engineering, University of Calgary, Calgary, Alberta, Canada
[c] BitCan Geosciences & Engineering Inc., Calgary, Alberta, Canada

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ABSTRACT

Thermal processes have been widely used to recover heavy oil from oil-sands reservoirs, where the overburden shale undergoes cyclic heating and cooling processes. During thermal operations, thermally induced pore pressure can be developed in the shale formation around a thermal well and thermal pore pressure may lead to plastic yielding in the shale. In this study, integrated characterization results on anisotropic thermal-hydro-mechanical (THM) properties of Colorado shale with different clay fractions are presented. Low strength shale intervals along a borehole are identified and the characterized results are used to conduct a stability analysis on an inclined wellbore during thermal operations. The effect of thermally induced pore pressure in Colorado shale on the integrity of a thermal well is investigated using 3D THM-coupled finite element analysis with the consideration of shale's transversely isotropic (TI) elastic characteristics. The results indicate that the wellbore can lose the confinement in high clay fraction shale intervals due to the thermal operation. The mechanisms can be caused by the thermal pore pressure-induced shear plastic yielding behavior in the Colorado shale formation. Tensile fracturing behavior is less likely to happen. The consideration of anisotropy in elastic properties is important in characterizing the shale's stress path in the analysis. Compared with the result based on the TI elastic model, the result based on the isotropic elastic model gives less plastic yielding zone which underestimates the risk.

1. Introduction

As one of the major thermal recovery processes, cyclic steam stimulation (CSS) has been applied to produce bitumen from the Clearwater formation in the Cold Lake area, Canada, since the 1960s. More than 3000 deviated wells have been used to inject high-pressure (> 10 MPa) and high-temperature ($> 300\,^{\circ}$C) steam to reduce the viscosity of the bitumen and produce reservoir fluids.[1] The Colorado shale formation overlying oil-sands reservoirs is of critical attention for wellbore stability analysis. Well casing failures in Cold Lake CSS projects have been observed using passive the seismic monitoring approach by Miyazawa et al.[2] As a typical soft mudrock, the Colorado group shale consists of an up to 180 m thick series of marine shales and minor siltstones, with some occasional ironstone, concretions, and bentonite layers. For the shale samples retrieved from the same geological formation, the clay fractions (particle size less than 2 μm) could have significant variations with burial depths.[1,3] Variations in amount and type of clay minerals present in soft mudrocks have contributed to their variations in fabric orientation distribution,[3] compression behavior,[4] swelling behavior,[5] strength,[5] permeability,[6,7] and thermal strain behavior.[8] The complex THM responses of soft mudrocks make the studies on wellbore stability challenging.[9] For an inclined borehole embedded in an anisotropic elastic formation, the stress distribution in the surrounding formation is affected by the anisotropy in elastic properties of the formation.[10–12] During the stage of steam injection, heat transferred from the casing to the surrounding Colorado shale formation at a high rate. The thermally induced pore pressure could be built up in high clay fraction shale intervals of low permeability. Thermally induced hydraulic fracturing could happen when the pore pressure is higher than the confining pressure plus shale's tensile strength.[13] The wellbore would lose its structural and hydraulic integrities when the surrounding shale failed. Due to limited characterization data on THM properties of Colorado shale, the risk of thermally induced pore pressure on wellbore integrity has not been evaluated for an actual CSS well at critical depths. Most attention was focused on the aspect of induced shear stresses in Colorado shale or bentonite seams caused by the reservoir

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[*] Corresponding author.
E-mail address: biao.li@concordia.ca (B. Li).

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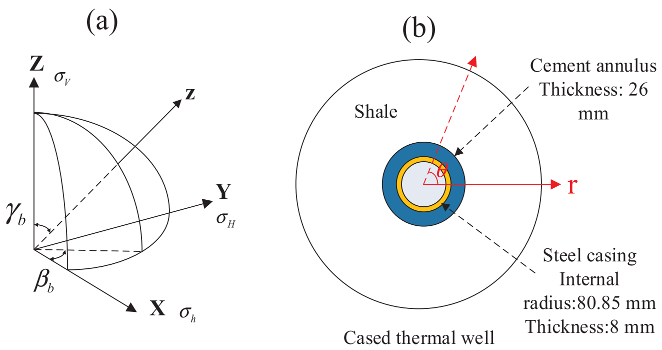

Fig. 1. (a) The inclination γ_b and azimuth β_b of an inclined borehole embedded in a shale formation (the bedding plane of shale formation is assumed to be parallel to the *X-Y* plane of in-situ stress). (b) The cross-section sketch of a cased thermal well (r and θ are radial coordinate).

dilation during steam injection.[1,14]

In this study, integrated characterization results on anisotropic THM properties of Colorado shale with different clay fractions are presented. The characterized results are used to conduct comprehensive stability analysis on an inclined borehole during thermal operations. The effect of thermally induced pore pressure in shale formation on wellbore integrity is investigated using a 3D THM-coupled finite element numerical analysis. The transversely isotropic (TI) elastic and plastic-yielding behavior of Colorado shale are considered.

2. Governing equations and constitutive models

The geomechanical simulation uses a coupled THM finite element formulation to consider the interactions between thermal transport, fluid flow, and mechanical deformation and failure. Thermal convection is ignored in the current formulation. According to Lewis et al.,[15] the governing equation can be formulated as:

$$\begin{cases}\nabla\cdot\left(\frac{\mathbf{k}}{\mu}\nabla p\right) = -\phi\beta_T\frac{\partial T}{\partial t} + \phi\beta_p\frac{\partial p}{\partial t} + (1-\phi)\frac{\partial\varepsilon_v}{\partial t}\\ \nabla\cdot(\mathbf{k}_T\nabla T) + \mathbf{q} = \rho c_T\frac{\partial T}{\partial t}\\ \nabla\cdot\boldsymbol{\sigma} + \mathbf{b} = 0\end{cases} \tag{1}$$

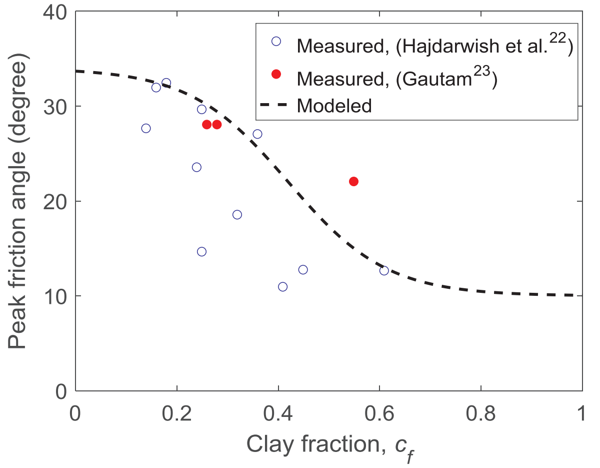

Fig. 3. Measured and modeled relationships between friction angles and clay fraction of some soft mudrocks.

where $\boldsymbol{\sigma}$ is the total stress tensor; $\mathbf{k}$ and μ are permeability tensor and viscosity of the total fluid phase, respectively. They should be understood as a combined term of $\mathbf{k}/\mu$ ratio (the total fluid mobility). ϕ is the porosity. β_p and β_T are pressure and thermal compressibility, respectively, again of the total fluid phase. ε_v is the rock's volumetric strain. $\mathbf{b}$ is the gravity term. $\mathbf{k}_T$ is the thermal conductivity tensor, ρ is the rock mass density, and c_T is its thermal capacity. $\mathbf{q}$ is a source term. Eq. (1) describes a coupled THM process and convection is not considered in the thermal transport equation. The thermal transport is decoupled from Eq. (1) by considering the assumptions: (1) The thermal convection effects can be ignored during the shale's mechanical failure; (2) The fluid flow and mechanical deformation do not change the thermal properties. Thus, Eq. (1) can be simplified to two equation systems: the fully coupled Biot consolidation problem and the thermal conduction problem.

We treat Colorado shale as a linear TI elastic material with an elastic-perfect plastic-yielding behavior. For TI material, five independent parameters are needed to characterize the anisotropic elastic stress-strain relation[16]:

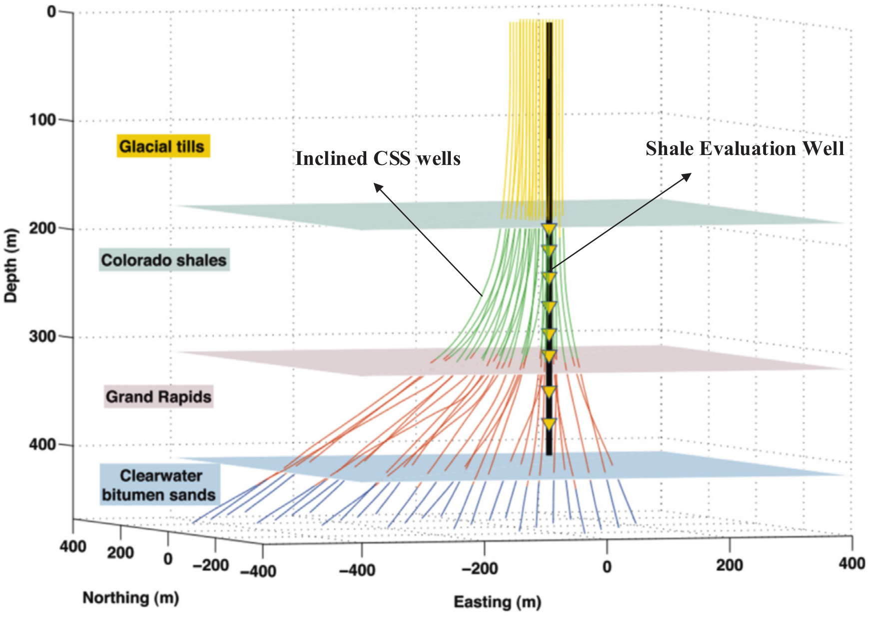

Fig. 2. Sketch showing CSS wells embedded in geological formations in the Cold Lake area, Alberta, Canada, modified after Miyazawa et al.[2]. The shale evaluation well was used to perform well logging analysis and to obtain shale samples.