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Research paper

Simulated geomechanical responses to marine methane hydrate recovery using horizontal wells in the Shenhu area, South China Sea

Guangrong Jin[a], Hongwu Lei[b], Tianfu Xu[a,*], Xin Xin[a], Yilong Yuan[a], Yingli Xia[a], Jinge Juo[c]

[a] Key Laboratory of Groundwater Resources and Environment, Ministry of Education, Jilin University, Changchun 130021, China
[b] State Key Laboratory of Geomechanics and Geotechnical Engineering, Institute of Rock and Soil Mechanics, China Academy of Sciences, Wuhan, Hubei 430071, China
[c] School of Civil and Environmental Engineering, Georgia Institute of Technology, 790 Atlantic Dr NW, Atlanta, GA 30313, USA

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ABSTRACT

The recovery of natural gas hydrate (NGH) from marine sediments faces challenging due to not only the gas productivity itself but also the possible geohazards, such as seafloor subsidence, submarine landslide, wellbore instability and possible sand production. The coupled thermal-hydrodynamic-mechanical (THM) processes during NGH recovery are generally complex, and numerical simulation tools are needed to assess related geomechanical responses. We have extended the Biot consolidation model in our previous simulator TOUGH2Biot, and incorporated into the existing TOUGH + hydrate code, resulting in a THM simulator for the NGH recovery. The THM simulator is used to assess the geomechanical responses to gas recovery from an unconfined hydrate-bearing sediment (HBS) in the Shenhu area, South China Sea. We investigated depressurization using constant bottom-hole pressure through a horizontal well. Results show that methane production quickly reaches a stabilized state and the water rate increases linearly. The drawdown of pore pressure around the well controls the increase in effective stress. Subsidence becomes significant after depressurization due to the quickly propagation of pore pressure. Depressurization in early stage could contribute to more than half of the total subsidence. The decreasing production pressure leads to an increase in the methane production rate but deterioration in subsidence. A decrease in intrinsic permeability of overlying and underlying layer is undesirable due to its decrease in methane production rate and the worse of subsidence. A balance between gas productivity and related geomechanical response must be achieved. The methods and preliminary results presented in this study could help us to understand the geomechanical behaviors during NGH recovery and to design trial production schemes under similar conditions.

1. Introduction

Natural gas hydrate (NGH) is a crystalline solid compound formed by gas molecules (such as methane, ethane, propane, and carbon dioxide) that occupy the cage structures of water molecules (Sloan and Koh, 2007; Liu et al., 2015a, 2015b). NGH has been found in either permafrost regions or deep ocean sediments (Max et al., 2005; Max and Johnson, 2014) where the ambient conditions of high pressure and low temperature are existed. As the large reserve of trapped natural gas, NGH is considered as a potential unconventional fossil fuel resource (Collett, 2002), and its recovery attracts a wide attentions from academic institutions, governments and oil companies (Moridis et al., 2009; 2011a).

Several methods, such as depressurization, thermal stimulation, inhibitor injection, are employed to destabilize hydrates by altering the conditions of pressure and/or temperature for NGH, and methane gas is then recovered through a production well (Jin et al., 2016; Zhang et al., 2010; Bhade and Phirani, 2015). Recent studies are conducted to reveal the mechanism, productivity and efficiency of these methods from laboratory-scale experiments to field trials (Kneafsey et al., 2007; Marinakis et al., 2015; McGrail et al., 2004; Yamamoto et al., 2014; Sun et al., 2014; Li et al., 2016; Moridis et al., 2011a). In 2013, the first offshore field trial was conducted in the Nankai Trough, Japan. Depressurization was technologically validated as feasible method and a total of 12000 m^3 of methane gas was recovered during the 6-day of production (Yamamoto et al., 2014). In general, depressurization by reducing the pressure in NGH formation is regarded as the most economic method (Moridis et al., 2011a; Zhang et al., 2010). Thermal stimulation is more suitable as an assisted approach, due to the costly heating, to improve production performance (Zhang et al., 2010; Moridis and Kowalsky, 2005; Reagan et al., 2014). The effect of inhibitor weakens because of the dilution of seawater. Gas exchange

* Corresponding author.
E-mail address: Tianfu_Xu@jlu.edu.cn (T. Xu).

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method is recently proposed by using CO_2 and/or N_2 to replace methane molecules in the cage structure (McGrail et al., 2004; White et al., 2011). However, the exchange rate highly depends on permeability.

In addition to the feasibility and efficiency of production, NGH recovery also arouses the concern of mechanical response due to the decreased pore pressure in hydrate-bearing sediment (HBS) (Rutqvist and Moridis, 2008; Gupta et al., 2015). Furthermore, the solid hydrate dissociates into mobile water and methane gas after hydrate dissociation, and the sediment strength and stiffness of the HBS decrease accordingly. This may causes seafloor subsidence, deterioration of wellbore stability and possible sand production (Uchida et al., 2016). Therefore, recovery of subsurface NGH involves thermal (T), hydraulic (H), mechanical (M) and chemical (especially when gas exchange) processes. Several simulators of TH processes, such as TOUGH + HYDRATE, STOMP-HYD, MH21-HYDRES and HydrateResSim (Moridis et al., 2008; White et al., 2011; Gupta et al., 2015), have been developed to assess the productivity of various methods. However, geomechanical responses were not considered in these numerical models. This study will focus on the coupled THM processes without considering the chemical gas exchange method.

To improve understanding of the geomechanical responses during NGH recovery, several simulators have been developed. TOUGH + HYDRATE code was incorporated with the commercial geomechanical code FLAC^{3D} by Rutqvist and Moridis (2008). Klar et al. (2010) used the FLAC to assess the effect of hydrates on the stress-strain behavior. Zhou et al. (2014) investigated deformation during the Nankai production trial.

Recently, a chemo-thermo-hydro-mechanical simulator using elasto-viscoplastic model was proposed to predict ground stability (Kimoto et al., 2010). Gupta et al. (2015) developed a hydro-geomechanical hydrate simulator by coupling fluid flow with linear elasticity. Stress and strain distributions were calculated for gas production from horizontal and vertical wells using the depressurization method (Rutqvist et al., 2012; Klar et al., 2010; Gupta et al., 2015). The effective stress increases in response to the depletion of pore pressure. Stress around well are driven by pressure depletion and this may reduce the integrity and stability of wellbore. Moreover, increased shear stress may cause shear failure in formation and grain detachment, which leads to sand production (Rutqvist et al., 2012; Uchida et al., 2016).

Recently, a 2D thermo-hydro-mechanical bonded contact model was proposed to study the changes of macro-scale and micro-scale mechanical behaviors by the distinct element method code, PFC2D (Jiang et al., 2016). The number of coupled THM simulations during hydrate dissociation has increased in recent years. However, there is still a need to further explore the geochemical response. A powerful simulator is the basis to improve our understanding of geomechanical behaviors in a complex geological setting and/or when using various production strategies. Furthermore, the geomechanical studies for the Shenhu area of South China Sea are rarely reported although some tri-axial tests have been investigated (Zhang et al., 2015; Sun et al., 2017).

This study takes module Biot of our previous THM simulator TOUGH2Biot (Lei et al., 2015) to characterize the mechanical behavior of HBS. The geomechanical module Biot is integrated into the existing TOUGH + hydrate code (Moridis et al., 2008), resulting in the specific THM simulator TOUGH + hydrate + Biot (simply called hydrateBiot) for the NGH recovery. The geomechanical response under depressurization through a horizontal well in Shenhu area is then investigated. The relationship between the geomechanical response and the gas productivity under different production pressure and permeability of bounded layer are discussed.

2. Modeling approaches

2.1. Governing equations for THM processes

The TOUGH + hydrate code (Moridis et al., 2008), which was developed by the Lawrence Berkeley National Laboratory, provides a reliable and open source base to simulate the thermo-hydrological processes during the NGH recovery. TOUGH + hydrate can simulate the transport of four components (water, CH4, hydrate, water-soluble inhibitors such as salts or alcohols) among four phases (gas phase, liquid phase, ice phase and hydrate phase), and also the non-isothermal dissociation of hydrate and heat flow. The governing equations of mass and energy balances used in TOUGH + hydrate are summarized in Table 1 (see Nomenclature for definitions of all symbols used).

Table 1
Governing equations of fluid and heat flow in TOUGH + hydrate.

Description	Equation
Mass and energy conservation	$\frac{d}{dt}\int_{V_n} M^{\kappa}dV = \int_{\Gamma_n} \mathbf{F}^{\kappa}\bullet\mathbf{n}d\Gamma + \int_{V_n} q^{\kappa}dV$
Mass accumulation	$M^{\kappa} = \sum_{\beta=A,G,I,H} \varphi S_{\beta}\rho_{\beta}X_{\beta}^{\kappa}, \quad \kappa = w, m, i, h$
Mass flux (aqueous phase)	$\mathbf{F}_A^{\kappa} = -k\frac{k_{rA}\rho_A}{\mu_A}X_A^{\kappa}(\nabla P_A - \rho_A\mathbf{g}), \quad \kappa = w, m, i$
Mass flux (Gas phase)	$\mathbf{F}_G^{\kappa} = -k\left(1 + \frac{b_{slippage}}{P_G}\right)\frac{k_{rG}\rho_G}{\mu_G}X_G^{\kappa}(\nabla P_G - \rho_G\mathbf{g}) + \mathbf{J}_G^{\kappa}, \quad \kappa = w, m$
Energy accumulation	$M^{\theta} = (1-\varphi)\rho_R C_R T + \sum_{\beta=A,G,H,I} \varphi S_{\beta}\rho_{\beta}U_{\beta} + Q_{diss}$
Heat flux	$\mathbf{F}^{\theta} = -\lambda\nabla T + \sum_{\beta=A,G} h_{\beta}\mathbf{F}_{\beta}$
Reaction heat of hydrate dissociation	$Q_{diss} = \begin{cases} \Delta(\varphi\rho_H S_H \Delta U_H) & \text{for equilibrium dissociation} \\ Q_H \Delta U_H & \text{for kinetic dissociation} \end{cases}$

To simulate the mechanical process, the Biot module of TOUGH2Biot (Lei et al., 2015) is extended to characterize the geomechanical response associated to the NGH recovery. Although the triaxial tests show that the stress-strain relationship of a hydrate-bearing sample is not expressed as elastic behavior (Zhang et al., 2015; Masui et al., 2008; Miyazaki et al., 2010, 2011), but the HBS can be regarded as elastic material as long as the range of application is sufficiently limited to small-strain cases far away from the critical state (Gupta et al., 2015). Based on the principle of effective stress (The effective stress, σ', is the difference between the total stress, σ, and the pore pressure, P_a, as $\sigma' = \sigma - \xi P_a$ and the ξ is the Biot' coefficient) and the assumption of linear elasticity, an extended Biot consolidation model with displacement as the primary unknown variables was formulated as shown in Table 2 (Lei et al., 2015). The effect of temperature change on stress is also considered in the model.

The strength increases linearly with hydrate saturation and also confining pressure, but the confining pressure has a minor effect. Therefore, the bulk modulus, shear modulus and cohesion are simply expressed as (Rutqvist et al., 2012):

$$K = (K_{SH1} - K_{SH0}) \times S_H + K_{SH0}$$

$$G = (G_{SH1} - G_{SH0}) \times S_H + G_{SH0}$$

$$c = (c_{SH1} - c_{SH0}) \times S_H + c_{SH0}$$

Where K_{SH0} and K_{SH1} are the bulk modulus without hydrate and when the hydrate saturation is 1, respectively. G_{SH0} and G_{SH1} are the shear modulus without hydrate and when the hydrate saturation is 1, respectively. c_{SH0} and c_{SH1} are the cohesion without hydrate and when the hydrate saturation is 1, respectively.

2.2. Coupling between TH and M

The coupled THM processes can be decoupled into the fluid flow and heat flow models (TH) and the mechanical model. The hydrateBiot inherits the fully coupled TH processes from TOUGH + hydrate. Stress and strain is obtained by solving the extended Biot mechanical