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Sand production model in gas hydrate-bearing sediments

Shun Uchida [a,*], Assaf Klar [b], Koji Yamamoto [c]

[a] Rensselaer Polytechnic Institute, 110 8th Street, Troy, NY 12180, USA
[b] Technion – Israel Institute of Technology, Technion City, Haifa 32000, Israel
[c] Japan Oil, Gas and Metals National Corporation, 1-2-2 Hamada, Mihama, Chiba 262-0019, Japan

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ABSTRACT

This paper provides a comprehensive analytical formulation that entails the features of sand production in gas hydrate-bearing sediments, including grain detachment, migration, sediment deformation and hydrate dissociation. The formulation is thermo-hydro-mechanically coupled such that grain detachment causes stress reduction, sediment shear deformation induces grain detachment and grain flow alters multiphase fluid pressure and temperature profiles. Through a series of analyses, the sensitivity of sand production related parameters on resulting solid volume changes is evaluated. Furthermore, the effect of various operational methods on mitigating sand production in hydrate-bearing sediments during gas production is numerically investigated. It is found that, out of the different operational methods investigated, lowering depressurization rate was the most effective in reducing sand production for a given gas production.

1. Introduction

Gas production from gas hydrate-bearing sediments has been attracting international interests because of its potential to meet growing global energy demand and to ensure energy security. Gas, however, has never been produced on a commercial scale due to the geomechanical complexity associated with the hydrate dissociation. To date, only a few short-term trials of gas production from hydrate-bearing sediments have been reported, most notably the trials conducted at the Mallik gas hydrate site, Canada, in 2007 and 2008[1] and at the Eastern Nankai Trough, Japan in 2013.[2] During the trials in 2007 and 2013, excessive amount of sand migration into the well occurred. This phenomenon is also known as sand production. Note that, in this paper, sand migration is used as a general term to represent the motion of flowing solids within the soil domain, while the term sand production is reserved for representing the ultimate state in which the flowing solids reach the well. The sand production during the two field trials prevented further gas production and the operations were prematurely terminated. These incidents have disclosed the adverse effect of sand production on gas extraction from gas hydrate-bearing sediments in a sustainable and controllable manner. They have also highlighted the importance of incorporating sand migration components into formulations of gas hydrate-bearing sediments to better predict and understand the mechanisms involved in gas and sand production.

Although several formulations exist for the representation of the coupled thermo-hydro-mechanical behavior of gas hydrate-bearing sediments (e.g. Refs. 3–5), as well as many sophisticated sand migration models (e.g. Refs. 6–12), there is no analytical work that treats the features of sand migration within gas hydrate-bearing sediments. Thus, this paper offers an analytical model for sand migration within gas hydrate-bearing sediments through further development and coupling of aforementioned thermo-hydro-mechanical models and sand migration models. The paper also discusses the possibility of mitigating sand production with various operational methods through a series of numerical analyses.

The paper is composed of four main sections. Firstly, a fully-coupled thermo-hydro-mechanical formulation including sand migration is developed. Secondly, the elastoplastic stress-strain relationship including grain detachment is presented. Thirdly, proposed models for grain detachment, settling and lifting are described. Lastly, the sensitivity analyses of each parameter on the solid volume changes with and without hydrate dissociation are presented. The last section also discusses the possibility of management of sand production through simulations of various operational methods. The validation of the developed model with sand production experiments on hydrate-free sediments conducted by Papamichos et al.[9] is provided as a supplementary material (at http://dx.doi.org/10.1016/j.ijrmms.2016.04.009).

2. Thermo-hydro-mechanical coupling

The effect of sand migration is included by extending the thermo-hydro-mechanical formulation for hydrate-bearing sediments by Klar et al.[5] In their work, the volume of solids (not soil skeleton) does not change unless thermally induced, based on the fact that soil grains

* Corresponding author.
E-mail address: uchids@rpi.edu (S. Uchida).

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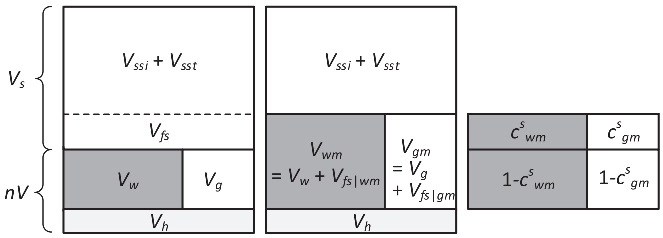

Fig. 1. An elementary volumetric cube representing solid states, mixture and concentrations.

are incompressible. Sand migration, however, alters the volume of solids. Thus, firstly, the mass balance equation for solids is presented. Subsequently, the coupled formulation is derived.

2.1. Solid mass balance

In order to consider sand migration, it is necessary to introduce three states for solid mass: (a) flowing solids that are currently flowing (*fs*); (b) stable solids that are still part of the original soil skeleton and thus intact (denoted as *ssi*); and (c) solids that are settled after flowing (*sst*). The mass balance equation of the solids is therefore expressed as:

$$m_s = m_{fs} + m_{ssi} + m_{sst} \tag{1}$$

where m is the mass per control volume and the subscripts s, fs, ssi and sst denote solids, flowing solids, intact solids and settled solids, respectively. A simple volumetric cube incorporating these states is shown in Fig. 1 where the subscripts w, g and h are for water, gas and hydrate, respectively. Flowing solids are assumed to travel with water or gas. Thus, the concept of mixture is introduced as water-flowing solid mixture (wm) and gas-flowing solid mixture (gm), respectively. The volumetric concentrations of the flowing solids in the water-mixture ($fs|wm$) and gas-mixture ($fs|gm$) are defined as $c^s_{wm} = \frac{V_{fs|wm}}{V_{fs|wm}+V_w}$ and $c^s_{gm} = \frac{V_{fs|gm}}{V_{fs|gm}+V_g}$ where V is the volume, which are also illustrated in Fig. 1.

The mixtures are assumed to hold the same superficial velocity as their corresponding fluids as commonly accepted by many other hydro-mechanical sand production models (e.g. Refs. 8–10), that is, $\mathbf{q}_{wm}/V_{wm} = \mathbf{q}_w/V_w$ and $\mathbf{q}_{gm}/V_{gm} = \mathbf{q}_g/V_g$ where $\mathbf{q}$ is the discharge vector. Assuming that the discharge of the sole fluid is governed by Darcy's law, the discharges of flowing solids, water and gas can be given by:

$$\mathbf{q}_{fs} = \mathbf{q}_{fs|wm} + \mathbf{q}_{fs|gm} = c^s_{wm}\mathbf{q}_{wm} + c^s_{gm}\mathbf{q}_{gm} = \frac{c^s_{wm}}{1-c^s_{wm}}\mathbf{q}_w + \frac{c^s_{gm}}{1-c^s_{gm}}\mathbf{q}_g \tag{2}$$

$$\mathbf{q}_w = -k^{thm}\frac{\mathbf{K}_h}{\mu_w}k^r_w(\nabla P_w - \rho_w\mathbf{g}) \tag{3}$$

$$\mathbf{q}_g = -k^{thm}\frac{\mathbf{K}_h}{\mu_g}k^r_g(\nabla P_g - \rho_g\mathbf{g}) \tag{4}$$

where μ is the viscosity, k^{thm} is a factor incorporating the change in the intrinsic permeability due to thermo-hydro-mechanical effects (described later in Section 2.4), $\mathbf{K}_h$ is the intrinsic permeability tensor with the effect of hydrate, k^r is the relative permeability factor derived from the model by van Genuchten,[13] P is the pressure, ρ is the density and $\mathbf{g}$ is the gravity vector.

The state of solids changes from intact (ssi) to flowing (fs) by grain detachment. The flowing solids may then change into settled (sst) by settling, or settled solids may flow again through lifting. Thus, the change in the flowing solid mass is given by:

$$dm_{fs} = -(dm_{ssi} + dm_{sst}) - \nabla\cdot(\rho_s\mathbf{q}_{fs})\,dt \tag{5}$$

Substituting Eq. (5) into the differential form of Eq. (1) results in:

$$dm_s = -\nabla\cdot(\rho_s\mathbf{q}_{fs})\,dt \tag{6}$$

This implies that the solid state change by itself does not alter the mass balance of solids. It is only changed by the mass divergence of flowing solids.

2.2. Coupled thermo hydro mechanical formulation including sand migration

The solid mass change alters the void volume as:

$$\frac{dV_v}{V} = \frac{d(V-V_s)}{V} = d\epsilon_v + \frac{\nabla\cdot(\rho_s\mathbf{q}_{fs})\,dt}{\rho_s} - (1-n)\beta_s\,dT \tag{7}$$

where ϵ_v is the volumetric strain (compression negative), n is the porosity ($=V_v/V$), β_s is the thermal expansion coefficient of soil grain and T is the temperature. Following the derivation presented in Klar et al.,[5] the solutions for dP_w, dP_g, dS_w, dS_g and dS_h can be obtained by:

$$\begin{aligned} dP_w = &-\frac{dt}{nD}\left[\frac{\nabla\cdot(\rho_w\mathbf{q}_w)}{\rho_w}\Gamma + \frac{\nabla\cdot(\rho_g\mathbf{q}_g)}{\rho_g}\right] - \frac{d\epsilon_v}{nD}\left[\frac{S_w\Gamma + S_g}{S_w+S_g}\right] \\ &+\frac{dt}{nD}\left[\frac{N_hM_w}{\rho_w}\Gamma + \frac{M_g}{\rho_g} - \frac{M_h}{\rho_h}\frac{S_w\Gamma+S_g}{S_w+S_g}\right]R_h(P_g,T) \\ &+\frac{dT}{D}\left[S_w\Gamma\beta_w + S_g\beta_g + \frac{S_w\Gamma+S_g}{S_w+S_g}\left(S_h\beta_h + \frac{1-n}{n}\beta_s\right)\right] \\ &-\frac{dt}{nD}\left[\frac{S_w\Gamma+S_g}{S_w+S_g}\right]\frac{\nabla\cdot(\rho_s\mathbf{q}_{fs})}{\rho_s} \end{aligned} \tag{8}$$

$$\begin{aligned} dP_g = &-\frac{dt}{nD}\left[\frac{\nabla\cdot(\rho_w\mathbf{q}_w)}{\rho_w} + \frac{\nabla\cdot(\rho_g\mathbf{q}_g)}{\rho_g}\overline{\Gamma}\right] - \frac{d\epsilon_v}{nD}\left[\frac{S_w + S_g\overline{\Gamma}}{S_w+S_g}\right] \\ &+\frac{dt}{nD}\left[\frac{N_hM_w}{\rho_w} + \frac{M_g}{\rho_g}\overline{\Gamma} - \frac{M_h}{\rho_h}\frac{S_w+S_g\overline{\Gamma}}{S_w+S_g}\right]R_h(P_g,T) \\ &+\frac{dT}{D}\left[S_w\beta_w + S_g\overline{\Gamma}\beta_g + \frac{S_w+S_g\overline{\Gamma}}{S_w+S_g}\left(S_h\beta_h + \frac{1-n}{n}\beta_s\right)\right] \\ &-\frac{dt}{nD}\left[\frac{S_w+S_g\overline{\Gamma}}{S_w+S_g}\right]\frac{\nabla\cdot(\rho_s\mathbf{q}_{fs})}{\rho_s} \end{aligned} \tag{9}$$

$$\begin{aligned} dS_w = &-\frac{dt}{nD}\left[\frac{\nabla\cdot(\rho_w\mathbf{q}_w)}{\rho_w}\frac{S_g}{K_g} - \frac{\nabla\cdot(\rho_g\mathbf{q}_g)}{\rho_g}\frac{S_w}{K_w}\right] \\ &-\frac{d\epsilon_v}{nD}\left[\frac{S_g}{K_g}S_w - \frac{S_w}{K_w}S_g - \frac{S_w}{K_w}\frac{S_w\Gamma+S_g}{S_w+S_g}S_h\right] \\ &+\frac{dt}{nD}\left[\frac{N_hM_w}{\rho_w}\frac{S_g}{K_g} - \frac{M_g}{\rho_g}\frac{S_w}{K_w} + \frac{M_h}{\rho_h}\frac{S_w}{K_w}\frac{S_w\Gamma+S_g}{S_w+S_g}\right]R_h(P_g,T) \\ &+\frac{dT}{D}\left[\frac{S_g}{K_g}S_w\left(\beta_w + \frac{1-n}{n}\beta_s\right) - \frac{S_w}{K_w}S_g\left(\beta_g + \frac{1-n}{n}\beta_s\right)\right. \\ &\left.-\frac{S_w}{K_w}\frac{S_w\Gamma+S_g}{S_w+S_g}S_h\left(\beta_h + \frac{1-n}{n}\beta_s\right)\right] \\ &-\frac{dt}{nD}\left[\frac{S_g}{K_g}S_w - \frac{S_w}{K_w}S_g - \frac{S_w}{K_w}\frac{S_w\Gamma+S_g}{S_w+S_g}S_h\right]\frac{\nabla\cdot(\rho_s\mathbf{q}_{fs})}{\rho_s} \end{aligned} \tag{10}$$