Geo-mechanics in hydrate reservoir simulation – an evaluation of thermally induced stresses and strains in a body of soil

Anuruddhika G. Jayasinghe & Jocelyn L.H. Grozic University of Calgary, Calgary, Alberta, Canada

ABSTRACT

Gas hydrate is the largest global reservoir of organic carbon; the amount of carbon captured being large as high as twice the amount of organic carbon available in the form of all other recoverable and non-recoverable fossil fuels. Gas production from hydrate reservoirs is associated with changes in pore fluid pressures and the stresses acting on the reservoir and surrounding rocks. This paper investigates the stress change behaviour and the subsequent deformation of hydrate bearing soil upon temperature induced dissociation (under undrained conditions) considering both mechanical and thermal loads.

RÉSUMÉ

L'hydrate de gaz est le plus grand réservoir global de carbone organique ; la quantité de carbone capturé est grande aussi deux fois que la quantité de carbone organique disponible sous forme de tous carburants de fossile autres, récupérables et irrécupérables. Gazer la production des réservoirs d'hydrate est associée avec les changements dans les pressions du fluide de pore et les tensions suivant le réservoir et les rochers environnants. Ce papier examine le comportement de changement de tension et la déformation subséquente d'hydrate portant du sol sur la température dissociation induite (sous undrained les conditions) considérant des chargements mécaniques et thermiques.

1 INTRODUCTION

Gas hydrate (clathrate) is formed as a result of encapsulation of gas molecules within parent lattices of hydrogen bonded water molecules. According to Hammerschmid (1994), as early as 1930s, pipeline blockages during natural gas transmission were identified as due to formation of hydrate, which encouraged the research community to focus more on gas hydrates. Naturally occurring gas hydrates were first observed in the Siberian Messoyakha gas field in 1960s (Makogon 1981) and researches carried out in 1970s discovered that occurrence of gas hydrates was not limited to onshore sediments but was common to deep water sediments as well (Claypool & Kaplan 1974). The investigations carried out since then reveal the abundant existence of gas hydrates in deepwater marine sediments as well as in the permafrost regions.

Gas hydrate is the most abundant form of organic carbon on the earth and the quantities are twice as large as that available in total reserves of recoverable and nonrecoverable fossil fuels including oil, gas, and coal combined (Kvenvolden 1993). Out of all other hydrate forms, methane hydrate is found to be the most common. The maximum amount of methane that can occur in a methane hydrate is fixed by the clathrate geometry. Most commonly, methane forms hydrates of molecular structure called Structure I. In a fully saturated Structure I methane hydrate, one molecule of methane is present for every 5 3/4 molecules of water. When appropriate hydrate expansion factors are considered, 1 volume of methane hydrate can generate 164.6 volumes of methane gas and 0.87 volumes of water (Figure 1) upon dissociation at standard temperature and pressure (Kvenvolden 1993).



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Figure 1: Cubic meter of methane hydrate yields 164.6 cubic meters of gas and 0.87 cubic meters of water at standard temperature and pressure (After Kvenvolden 1993)

At least three methods for gas recovery from hydrates are extensively subject of discussions; (1) thermal stimulation, (2) depressurization, and (3) inhibitor injection. Thermal stimulation, in which the temperature is raised beyond the equilibrium temperature at the existing pressure, considers employing the techniques such as cyclic injection of a hot fluid (such as steam, water, or brine) into the hydrate bearing formation, and combustion of a liquid fuel and an oxidant within the formation. The depressurization technique focuses on reducing the pressure to a level lower than the equilibrium pressure at the existing temperatures while a shift in the hydrate stability conditions is achieved by inhibitor injection. Irrespective of the method employed, hydrate dissociation results in a change in the stress state and a subsequent deformation within the host sediment and therefore, the geo-mechanics of hydrate bearing sediments cannot be exempted from discussion. On the one hand, hydrate

formation/dissociation is conditioned by the host sediment properties while, on the other hand. the strength/deformation behaviour of the host sediment is conditioned by the mere presence of hydrate within its pore space and the dissociation of the same. In fact, the equilibrium pressure at a given temperature is raised by capillary effects. The finer the pore radius, the greater the increment in equilibrium pressure would be. According to the experimental investigation by Handa and Stupin (1992), the temperature-pressure profiles measured for methane and propane hydrates in silica gel pores revels 20 and 100% increases in equilibrium pressures respectively relative to those for the bulk hydrates. This paper focuses on the geo-mechanical behaviour of the host sediment upon temperature induced dissociation of hydrate and avoids further discussion of thermodynamic stability affected by the sediment properties. The following section reviews the few existing reservoir simulation models for gas production from thermal stimulation and emphasizes on the need to couple the soil deformation problem with the hydrate dissociation problem.

2 GEOMECHANICS IN RESERVOIR SIMULATION

Selim and Sloan (1989) modeled the dissociation process in one dimension to provide an analytical solution and the dissociation process was induced by a temperature rise at the boundary of a semi-infinite region. The finite element model developed by Das and Srivastava (1993) considers heat transfer in the form of conduction while ignoring the convective component of heat transfer. The model addresses the dissociation problem in cylindrical geometry with heat transfer in radial and vertical directions and is applicable for low-porosity medium where the convective component of the heat transfer process could be neglected at a minimal expense of accuracy. Scott et al. (2006) developed a finite element model with consideration given to both conductive and convective heat transfer. In the aforementioned model the dissociation of hydrates releases gas and water at a Stefan like moving boundary. It is important to note that the all aforementioned models are based on the intrinsic assumption that hydrate bearing soil medium is undeformable and/or remains unaffected by the dissociation process. Thus, the most significant contributions to date have been towards the better understanding and/or representation of the heat and mass transfer processes in porous media.

Recently, geo-mechanics has received attention as a necessary, essential, and often absent component in reservoir simulation studies. Tsypkin (2000) recognized the need to incorporate the influence of interfacial forces between rock material, hydrates and fluids in further studies. Experimental evidence also supports the existence of a relationship between the hydrate dissociation and the soil behavior; the changes in soil strength and deformation. Jayasinghe and Grozic (2007) experimentally investigated the temperature induced dissociation behavior of methane hydrate within the pores of a cylindrical soil specimen in a triaxial testing configuration under undrained conditions (meaning the pore fluid pressure dissipation process is significantly slow relative to the hydrate dissociation process). The results indicated that the quantities of gas and water generated by hydrate decomposition result in an increase in the pore fluid pressures, eventually causing drastic reductions in *effective stress* leading to sediment failure. The term *effective stress* is used here to represent a stress change in which a responsive deformation or volume change behavior in soil is expected to be observed. In addition to the aforementioned changes in the stress state, the specimen was observed to undergo a volume expansion as the hydrates dissociate, which is indicative of the pore fluid compressibility/expansibility of hydrate bearing sediments.

3 STRESSES IN SOIL

To facilitate the explanation of the state of stress at a given point in a soil mass, a small element of soil in the neighbourhood of the point in concern is considered. The sides of the element are considered to be parallel with the co-ordinate axes. According to Biot (1941), "...this element is taken to be large enough compared to the size of the pores so that it may be treated as homogeneous," (a body in which the material constants such as Young's modulus E, are the same at all points) "and at the same time small enough, compared to the scale of macroscopic phenomena in which we are interested so that it may be considered as infinitesimal in the mathematical framework". Consequently, the stress state at a point $[\sigma_{ii}]$, could be defined in terms of the normal and shear components of stress in the respective Cartesian co-ordinate directions.

$$\sigma_{ij} = \begin{vmatrix} \sigma_{xx} & \sigma_{yx} & \sigma_{zx} \\ \sigma_{xy} & \sigma_{yy} & \sigma_{zy} \\ \sigma_{xz} & \sigma_{yz} & \sigma_{zz} \end{vmatrix}$$
[1]

The notation σ_{ij} , is interpreted as the stress acting in the co-ordinate direction of j on the plane normal to the co-ordinate direction i. The normal stresses σ_{ij} (i = j), are denoted as $\sigma_{ij} = \sigma_i$ in the following text. The stresses σ_{ij} are considered to be comprised of a hydrostatic component of stress which is caused by the average pore fluid pressure p, and a component of average skeleton stress which is previously referred to as the *effective stress*.

4 SOIL DEFORMATIONS (STRAINS)

Mechanical strains occur in a body of soil as a consequence of changes in the state of stress. A change in the state of stress at a given point within a soil mass could be attributed to one or more events including changes in the stresses applied at the boundary, changes in contact level stresses such as the stresses induced due to capillary effects, changes in skeletal stress due to stresses induced by a change in the chemical-thermodynamic state of the body, etc. In addition to mechanical strains, thermal strains could also occur as a consequence of thermal expansion/contraction of the constituent materials. The following considers an element of hydrate bearing soil and investigates the deformation behaviour upon temperature induced dissociation of hydrate.

Let us consider an element of soil of initial total volume of V_{To} ; the pore space is comprised of hydrate, water and gas (Figure 2), and the initial soil consistency is given as follows:

$$V_{To} = V_{so} + V_{wo} + V_{go} + V_{Ho}$$
[2]

where V_{so} , V_{wo} , V_{go} , and V_{Ho} denote initial volume of solid soil, volume of water, volume of free gas, and the volume of hydrates respectively.



Figure 2: The soil structure and its consistency for a hydrate bearing soil

The initial temperature before the incremental change in the state of the system is denoted by T_o . The initial void ratio e_o , porosity φ_o , degree of water saturation S_{Wo} , degree of gas saturation S_{Go} , and the hydrate content, η_o , are defined as below.

$$e_o = \frac{V_{vo}}{V_{so}}, \ \varphi_o = \frac{V_{vo}}{V_{To}}, \ S_{Wo} = \frac{V_{wo}}{V_{vo}},$$
$$S_{Go} = \frac{V_{go}}{V_{vo}}, \ \eta_o = \frac{V_{Ho}}{V_{vo}}$$
[3]

The parameter $V_{\nu a}$ denotes the initial void volume.

The process of entirely temperature induced hydrate dissociation does not involve changes in mechanical loads applied at the boundary, however, the differential thermal expansion of the constituent materials and, the decomposition of hydrates into gas and water (which then results in a change in the soil system consistency), both generate changes in average pore fluid pressure. The average skeleton stress will then be altered and strains induced. Therefore, the total strain could be viewed as the addition of the two strain components caused by the thermally induced mechanical loads and, the thermal loads (expansion/contraction). The strains due to induced mechanical loads could be expressed by applying the Hook's law for a linear elastic homogeneous, isotropic material for the soil medium neglecting non-linear elasticplastic behavior of soil while, the strains due to thermal loads can be expressed in terms of the coefficient of linear thermal expansion, α_L of the medium.

$$\varepsilon_{xx} = \frac{1}{E} [\sigma'_{xx} - \mu(\sigma'_{yy} + \sigma'_{zz})] + \alpha_L \tau$$

$$\varepsilon_{yy} = \frac{1}{E} [\sigma'_{yy} - \mu(\sigma'_{zz} + \sigma'_{xx})] + \alpha_L \tau$$

$$\varepsilon_{zz} = \frac{1}{E} [\sigma'_{zz} - \mu(\sigma'_{xx} + \sigma'_{yy})] + \alpha_L \tau$$

$$\gamma_{zx} = \frac{1}{G} \sigma_{zx}, \quad \gamma_{yz} = \frac{1}{G} \sigma_{yz}, \quad \gamma_{xy} = \frac{1}{G} \sigma_{xy} \qquad [4]$$

The volumetric strain,

$$\Delta V_T / V_{To} = \varepsilon_v = \varepsilon_{xx} + \varepsilon_{yy} + \varepsilon_{zz}$$
^[5]

Shear modulus,
$$G = \frac{E}{2(I+\mu)}$$
 [6]

The parameter, τ denotes the change in temperature with respect to the reference temperature (T_o); The current temperature within the soil element is denoted by T.

$$\tau = T - T_o$$
^[7]

Rearranging the set of equations (4) into the following form, the constitutive equations for hydrate bearing thermo-elastic soil could be written as follows. The parameter p denotes the average pore fluid pressure.

$$(\sigma_r - p) = \sigma'_r = \lambda \varepsilon_v + 2G\varepsilon_r - \beta \tau$$
$$(\sigma_\theta - p) = \sigma'_\theta = \lambda \varepsilon_v + 2G\varepsilon_\theta - \beta \tau$$

$$(\sigma_{z} - p) = \sigma'_{z} = \lambda \varepsilon_{v} + 2G\varepsilon_{z} - \beta \tau$$

$$\sigma_{zr} = G\gamma_{zr}$$

$$\sigma_{\theta z} = G\gamma_{\theta z}$$

$$\sigma_{r\theta} = G\gamma_{r\theta}$$
[8]

The Lame's constant λ , and a material parameter for a soil undergoing elastic deformations under the application of thermal loads β could be defined as follows.

$$\lambda = \frac{\mu E}{(1+\mu)(1-2\mu)}, \ \beta = \frac{\alpha_L E}{(1-2\mu)}$$
[9]

It is important to note that the pore fluid compressibility of the hydrate bearing medium cannot be considered negligible, since the pore fluid may contain a considerably large volume of free and dissolved gas. Further, dissociation of hydrate results in a significant increase in the volume percentage of the gas component within the pore space. Booker and Savvidou (1985) developed the governing equations for a saturated twophase (Soil and water) thermo-elastic soil undergoing subsequent consolidation upon an increment of temperature. The compressibility of the constituent materials was neglected and the change in the volume of the element plus any increase in the volume (due to the increase in temperature) of the constituents was matched with the volume outflow from the soil element. A similar approach could be adopted for hydrate bearing soils provided that the volume change due to the compressibility of the constituents is accounted for. The following constructs a mathematical relationship between the average pore fluid pressure p, and the total volumetric strain considering both compressibility and thermal expansion of the constituents.

Given a change $\varDelta p$ in the average pore fluid pressure due to differential thermal expansion and the dissociation of hydrate, and an increment in temperature $\varDelta T$, the soil element deforms resulting in a volumetric strain of $\varDelta V_T \, / V_{To}$. The total volume change in the specimen could be equated to the summation of the component volume changes. Undrained conditions are assumed and the pore fluid generated form hydrate dissociation retains within the boundaries of the soil element in consideration.

$$\Delta V_T = \Delta V_s + \Delta V_w + \Delta V_g + \Delta V_H$$
^[10]

The volume change of the solid soil phase:

$$\Delta V_s = m_{vs} V_{so} \Delta p + 3\alpha_{Ls} V_{so} \Delta T$$
^[11]

The volume change in the aqueous phase:

$$\Delta V_w = \Delta V_{wc} + \Delta V_{wt} + \Delta V_{wH}$$
^[12]

Volume change due to water compressibility:

$$\Delta V_{wc} = m_{vw} V_{wo} \Delta p_w$$
[13]

Volume change due to thermal expansion of water:

$$\Delta V_{wt} = \alpha_w V_{wo} \Delta T$$
[14]

Volume change due to the amount of water generated from dissociation of hydrates:

$$\Delta V_{wH} = V_l \frac{\Delta V_{HH}}{V_e}$$
[15]

The volume change in gas phase:

$$\Delta V_g = \Delta V_{gc} + \Delta V_{gH}$$
^[16]

Volume change due to gas compressibility:

$$\Delta V_{gc} = V_g - V_{go}$$
[17]

Assuming the ideal gas law for the gas component, free gas volume $V_{\rm g}$, is expressed as follows.

$$V_g = \frac{p_{go} V_{go} T}{p_g T_o}$$
[18]

Volume change due to the amount of gas generated from dissociation of hydrates:

$$\Delta V_{gH} = \frac{RT}{p_g} \frac{l}{n_k} \frac{\Delta V_{HH}}{V_e}$$
[19]

This volume component $\varDelta V_{gH}$, is computed by applying the ideal gas law to the number of gas moles removed from the hydrate phase due to dissociation of hydrates.

Volume change due to the dissociated amount of hydrates:

$$\Delta V_H = \Delta V_{HH} = \varphi \eta V_{To}$$
^[20]

The average pore fluid pressure p, is defined for the hydrate system in terms of the degree of water saturation S_W , and the degree of gas saturation S_G of the medium as follows.

$$p = \left(\frac{S_W}{S_G + S_W}\right) p_w + \left(\frac{S_G}{S_G + S_W}\right) p_g$$
[21]

 p_{w} and p_{g} represents pore water pressure and pore gas pressure respectively.

The average pore fluid pressure $^{p}% \left(p\right) =0$, is approximated by,

$$p = \left(\frac{S_{Wo}}{S_{Go} + S_{Wo}}\right) p_{W} + \left(\frac{S_{Go}}{S_{Go} + S_{Wo}}\right) p_{g}$$
[22]

Considering capillarity action in porous soil media, the relationship between p_w and p_g can be expressed as follows.

$$(p_g - p_w) = \frac{2\sigma_T Cos\alpha}{r_p}$$
[23]

Combining equations [22] and [23], the following relationships can be obtained.

$$p_w = p - p'_g$$
 Where $p'_g = \frac{S_{Go}}{S_{Wo} + S_{Go}} \frac{2\sigma_T Cos\alpha}{r_p}$

$$p_{g} = p + p'_{w}$$
 Where $p'_{w} = \frac{S_{Wo}}{S_{Wo} + S_{Go}} \frac{2\sigma_{T}Cos\alpha}{r_{p}}$ [24]

Substituting the equations [11] - [24] in equation [10], an expression for the volumetric strain in terms of the average pore fluid pressure p, is obtained and takes the following form.

$$\varepsilon_{v} = \Delta V_{T} / V_{To} = \frac{1}{V_{To}} p[m_{vs}V_{so} + m_{vw}V_{wo}]$$

+ $\frac{1}{V_{To}} \frac{1}{p + p'_{w}} \left[\frac{\varphi_{o}\eta_{o}V_{To}RT}{n_{k}V_{e}} + \frac{p_{go}V_{go}T}{T_{o}} \right]$
- $\frac{1}{V_{To}} [m_{vs}V_{so}p_{o} + m_{vw}V_{wo}(p_{wo} + p'_{g})]$
+ $\frac{1}{V_{To}} [\varphi_{o}\eta_{o}V_{To}(\frac{V_{l}}{V_{e}} - 1) - V_{go}]$
+ $\frac{\Delta T}{V_{To}} [3\alpha_{Ls}V_{so} + \alpha_{w}V_{wo}]$ [25]

It should be noted that the volume change due to gas dissolution in water has not been included in the above volume change analysis as it is considered negligible. The volume analysis takes into account the combined effect of differential thermal expansion and the hydrate decomposition over the stress change and deformation processes.

5 DISCUSSION

This paper emphasizes on the essential and necessary role geo-mechanics is playing in hydrate reservoir simulation and derives the mathematical formulation of a method to quantify the soil deformation due to the combined effect of mechanical and thermal loads. The undrained conditions are assumed. The future work will consider porous media flow effects when drained conditions prevail. In an age of seeking new energy resources, understanding the behaviour of soils containing gas hydrates is fundamental to the development of ways and means of recovering vast gas resources existing in the form of hydrates. The knowledge geo-mechanical response of hydrate bearing of sediments will enable better estimates of benefits and risks associated with the recovery processes ensuring safe and economical exploration.

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NOMENCLATURE

E	Young's Modulus [Pa]
G	Bulk modulus [Pa]
m_v	Compressibility modulus [Pa ⁻¹]
n_k	Number of water moles per gas mole in the
	hydrate phase
p	Fluid pressure [Pa]
R	Ideal gas constant [JK ⁻¹ mol ⁻¹]
r_p	Mean pore radius [m]
S_G	Degree of gas saturation
S_W	Degree of water saturation
Т	Temperature [K]
V	Volume [m ³]
V_T	Total volume [m ³]
V_{e}	Molar volume of water in the hydrate phase
C	[m ³ mol ⁻¹]
$V_{}$	Total void volume which is occupied by hydrates,
V	pore water, and free gas [m ³]
V_i	Partial molar volume of water in the solution
l	$[m^{3}mol^{-1}]$
α	Wetting angle [rad]
α_L	The coefficient of linear thermal expansion [K ⁻¹]
α_{Is}	The coefficient of linear thermal
Lo	expansion for solid soil [K ⁻¹]
α	The coefficient of thermal expansion
W	for water [K ⁻¹]
β	A material property for thermal expansion [PaK ⁻¹]

γ	Shear strain
Δ	Increment
ΔV_{gc}	Volume change due to gas compressibility under
	the isotropic pore gas pressure p_{g} [m ³]
$\varDelta V_{gH}$	Volume change due to gas generated by
	dissociation of gas hydrate [m ³]
$\Delta V_{_{Hc}}$	Volume change due to compressibility of the
	hydrate phase under the isotropic pore fluid pressure $p [\text{m}^3]$
$\Delta V_{\rm HH}$	Volume change due to the dissociated amount
	of hydrates [m ³]
$\Delta V_{_{\scriptscriptstyle WC}}$	Volume change due to water compressibility
	under the isotropic pore water pressure $p_{\scriptscriptstyle W}[{\rm m}^3]$
$\Delta V_{_{wH}}$	Volume change due to water generated by
	dissociation of gas hydrate [m ³]
ΔV_{wt}	Volume change due to the thermal expansion of
Е	water [m ³]
8	Volumetric strain
2	Lamo's constant [Pa]
μ	Poisson's ratio
n n	Hydrate content
σ	Stress on a plane [Pa]
-	

- σ' Effective stress [Pa]
- σ_T Surface energy per unit area [Jm⁻²]
- *φ* Porosity

Subscripts

- g Gas phase
- H Hydrate phase
- *h* Hydrate zone
- *ij* On a plane perpendicular to i in the direction of j where i, j = x, y, z
- *o* Initial condition
- s Solid soil phase

- w Water phase
- *x* Co-ordinate direction *x*
- *y* Co-ordinate direction *y*
- *z* Co-ordinate direction *z*

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