Variance-based determination of dominant model parameters for sand migration in homogeneous gas hydrate-bearing reservoir

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\textbf{ABSTRACT}

Sand migration in gas hydrate-bearing reservoir poses a serious problem for a successful long-term gas production. Because gas production is achieved through hydrate dissociation, often driven by depressurization, the process of sand migration involves highly coupled multiphysics behavior. For example, hydrate dissociation causes sediment deformation and may increase the potential of sand migration but hydrate dissociation can also increase permeability, which may lower hydraulic gradient at a given flow rate, leading to reduction in sand migration. Other factors include that sand inflow (or outflow) would cause the increase (or decrease) in pore pressure due to void volume change and thus may halt (or accelerate) hydrate dissociation. An analytical thermo-hydro-mechanical sand migration model to incorporate these interacting features requires a number of parameters and it is important to quantify the significance of each parameter to this complex process of sand migration in gas hydrate-bearing reservoir. This study, therefore, conducts a series of sand migration analyses in field-scale homogeneous gas hydrate-bearing reservoir subjected to depressurization and presents the relative importance of each parameter to the volume of produced sand from a production zone. It is found that the volume of produced sand is mostly dominated by the parameter converting shearing deformation to sand detachment potential and by the parameter increasing critical hydraulic gradient for sand detachment with hydrate saturation.

\textbf{Keywords:} gas hydrates, sand migration, coupled thermo-hydro-chemo-mechanical model, variance-based sensitivity analysis

\section{INTRODUCTION}

A long-term gas production from gas hydrate-bearing reservoir still remains a major challenge and one of the inhibiting factors is sand migration problem. If not controlled properly, the sand migration can reach an excessive state and may lead to early shutdown of the gas production operation as has been observed in the past (e.g. Dallimore et al., 2012 and Yamamoto et al., 2014). As a part of MH21, Research Consortium for Methane Hydrate Resources in Japan, Uchida et al. (2016a) developed the analytical thermo-hydro-mechanical sand migration model and, because of highly coupled nature in the evolution of sand migration within gas hydrate-bearing sediments, the model requires six parameters. The model was applied to conduct several case studies and one of the key findings was that shearing deformation caused by non-uniform hydrate dissociation contributed to sand migration both in magnitude and duration (e.g. Uchida et al., 2018). In Uchida et al. (2016a), the sensitivity of sand migration to each parameter was evaluated but it only considered a very thin layer with uniform hydrate dissociation. Therefore, this study examines the effect of each parameter on sand migration in a field-scale reservoir that induces non-uniform hydrate dissociation. This paper first presents a brief overview of the sand migration model and the physical meaning of the six parameters. Secondly, the results of sand migration analyses in gas hydrate-bearing reservoir and also the effect of parameter variations on sand migration are discussed. Furthermore, the relative importance of each parameter to the produced sand volume is quantified through variance-based sensitivity analysis, leading to determination of the dominant parameters.

\section{OVERVIEW OF SAND MIGRATION MODEL}

Gas hydrate-bearing sediments consist of solid (or sand grains) and void and inside the void there occurs
water, gas and hydrate. The solid is commonly treated as immobile but when sand migration happens they transport. Considering that a part of solid would become mobilized, the sand migration model by Uchida et al. (2016a) introduces three states for the solid:

\[ V_s = V_{ssi} + V_{ssw} + V_{fs} \] (1)

where \( V_s \) is the solid volume, \( V_{ssi} \) is the volume of intact solid, \( V_{ssw} \) is the volume of settled solid and \( V_{fs} \) is the volume of flowing solid. It should be noted that, although hydrate is a solid-phase, \( V_s \) only considers the volume of soil solid phase, in this case, sand grains. The initiation of sand migration is the state change from the intact, \( V_{ssi} \), to flowing, \( V_{fs} \), and is termed as grain detachment. Grain detachment is assumed to occur when the hydraulic gradient becomes greater than its critical value. The magnitude of the detached solid volume is assumed to depend on the current intact solid volume and the quantity called detachment potential. In Uchida et al. (2016a), the detachment can be driven by both water and gas but for simplicity this study considers only water-driven grain detachment. This leads to a simplified mathematical expression for the detachment:

\[ dV_{ssi} = -V_{ssi} \alpha_2 M^{dxc} H \left( \frac{i_w}{i_0} - 1 \right) dt \] (2)

where \( \alpha_2 \) is the parameter incorporating the rate of detachment, \( M^{dxc} \) is the detachment potential, \( H(x) \) is the heaviside step function, \( i_w \) is the size of the hydraulic gradient of water (\( = i_0 \)), \( i_w^{crit} \) is the critical hydraulic gradient above which detachment occurs and \( t \) is time. In a similar concept to the mechanism of liquefaction triggered by cyclic shear strain (e.g. Dobry and Abdoun, 2017), the detachment potential is considered to increase with shearing deformation:

\[ M^{dxc} = \alpha_4 \varepsilon_d + \ln \left( \frac{V_{ssi}}{V_{\phi i}} \right) \] (3)

where \( \alpha_4 \) is the parameter converting deviator strain, \( \varepsilon_d \), to the detachment potential and \( V_{\phi i} \) is the initial intact solid volume. Eq. (3) states that the potential increases with shearing deformation but the detachment itself depletes the potential.

Upon grain detachment, in addition to the state change, the sand migration model by Uchida et al. (2016a) assumes that it causes the effective stress reduction. This is because the detached solid no longer carries the effective stress. For simplicity, it is assumed that the effective stress reduction (\( \partial \sigma / \sigma' \)) is proportional to the intact solid volume reduction (\( dV_{ssi} / V_{ssi} \)):

\[ \frac{\partial \sigma}{\sigma'} dV_{ssi} = \alpha_1 \sigma' dV_{ssi} \] (4)

where \( \alpha_1 \) is the proportionality factor.

The presence of solid-phase hydrates is known to increase stiffness, strength and dilatancy of the host sediments (e.g. Yoneda et al., 2015; 2017). This can be viewed as the increase in interlocking of soil so that the hydrates should add resistance against host soil’s grain detachment. The critical hydraulic gradient is thus assumed to increase with hydrate saturation by:

\[ i_w^{crit} = i_w^{crit} (1 - S_h)^{-\alpha_5} \] (5)

where \( i_w^{crit} \) is the critical hydraulic gradient when fully-water saturated and \( S_h \) is the hydrate saturation.

The transportation of flowing solid, \( V_{fs} \), is governed by the Darcy’s law under the assumption that the flowing solid and the pore water hold the same volumetric flux, that is:

\[ q = \frac{V_{fs}}{V_w} q_w \] (6)

where \( q \) and \( q_w \) are the discharge vector of flowing solid and water, respectively and \( V_w \) is the pore water volume. The flowing solid, \( V_{fs} \), may settle and become settled solid, \( V_{ssw} \), whereas the settled solid can be lifted and be flowing again. These state changes occur at a lower hydraulic gradient than the critical hydraulic gradient for detachment such that:

\[ dV_{ssw} = V_{fs} H \left( 1 - \frac{i_w}{\alpha_3 i_w^{crit}} \right) dt - V_{ssw} H \left( \frac{i_w}{\alpha_3 i_w^{crit}} - 1 \right) dt \] (7)

where \( \alpha_3 \) is the reduction factor for settling/lifting and the value is between 0 and 1. The first term of Eq. (7) represents settling and the second term represents lifting.

Altogether there are six parameters in the sand migration model by Uchida et al. (2016a). Table 1 summarizes the notation, its physical meaning and the corresponding equation number. It also contains the mean values adopted for the subsequent analyses. Ideally, these values should be carefully calibrated but there are little data available. Therefore, the values utilized for this study do not represent any specific site conditions and are simply selected for the purpose of the analyses. The uncertainties involved in the parameters are, however, incorporated by the means of variability for the analyses. For a fair comparison, these parameters are assumed to have 25 % coefficient of variation.

| Notation | Description | Eq. no. | Mean value |
|----------|-------------|---------|------------|
| \( \alpha_1 \) | Effective stress reduction due to grain detachment | (4) | 2.0 |
| \( \alpha_2 \) | Rate for grain detachment | (2) | 0.1 (hour−1) |
| \( \alpha_3 \) | Increase in \( i_w^{crit} \) with hydrate | (2), (5), (7) | 3.0 |
| \( \alpha_4 \) | Shearing deformation to detachment potential | (3) | 1.0 |
| \( \alpha_5 \) | Settling/lifting grain reduction | (7) | 0.5 |
| \( i_w^{crit} \) | Critical hydraulic gradient when water-saturated | (2), (5), (7) | 5.0 |
3 SAND MIGRATION ANALYSES FOR HOMOGENEOUS GAS HYDRATE-BEARING RESERVOIR

Sand migration is found to be affected by non-uniform hydrate dissociation (Uchida et al., 2018). To incorporate non-uniform hydrate dissociation within a simple setting, this study considers a two-dimensional axisymmetric homogeneous gas hydrate-bearing reservoir with a limited production zone. The following subsections describe the model geometry and model parameters adopted in the analyses, followed by simulation results and discussions.

3.1 Model geometry and initial conditions

Fig. 1 shows the model geometry considered in this study. There is a 5-meter-thick production zone within 50-meter-thick, axisymmetric (initially) homogeneous gas hydrate-bearing sediments. The top and far-field (right-hand) end of the model boundaries are supported by the constant total stresses, so that they can move both radially and vertically. The well boundary is radially fixed and the bottom end of the model boundary is vertically fixed. The top, bottom and far-field boundaries are assumed to have the constant pore water pressure and temperature, allowing fluid and thermal flow. The well boundary is assumed to be insulated (no thermal flow) and impermeable (no fluid flow), except the production zone. In other words, the well is supported but open for fluid production. Migrating sands are also free to flow into the well from the production zone.

The top end of the model boundary is assumed to be located at 1275 m below sea level (bsl) and 275 m below sea floor (bsf). The initial pore water pressure and total stresses are assumed to be hydrostatic and geostatic, leading to \( P_{w0} = 12.75 \text{ MPa} \) and \( \sigma_{z0} = 2.75 \text{ MPa} \) at the top of the model boundary. The temperature at the top of the model boundary is \( T = 11.25 \, ^\circ\text{C} \) and increases with 0.03 °C/m gradient. This leads to the phase equilibrium pressure of gas hydrates \( P_{eq} \) being approximately \( 9.8 \text{ MPa} \) near the production zone. The initial porosity is \( n_0 = 0.4 \) and the initial intrinsic permeability is \( |K| = 10^{-12} \text{ m}^2 \) (\( \approx 1 \text{ Darcy} \)), which will fall (or rise) according to the decrease (or increase) in the porosity. The effective permeability evolves with hydrate saturation according to a simple power law (Masuda et al., 1995) and this study uses the power of 5, resulting in \( K_h = K(1-S_h)^5 \). The initial hydrate saturation is \( S_{h0} = 0.5 \).

3.2 Soil model parameters and sand migration model parameters

For mechanical behavior of gas hydrate-bearing sediments, this study adopts the methane hydrate critical state model by Uchida et al. (2012; 2016b). The highlight of the model is its introduction of hydrate-dependent strength parameter, \( p'_{cd} \), to expand the yield surface of the host soil, leading to stronger and more dilatant soil at a given stress state \((p', q)\) as shown in Fig. 2a, where \( q \) is the deviator stress, \( p' \) is the mean effective stress, \( M \) is the stress ratio at the critical state and \( p'_{cs} \) is the strength parameter of the host soil, also known as preconsolidation stress. Due to \( p'_{ed} \) the hydrate-bearing soil also has a greater volumetric yielding strength at which the volumetric response changes from the slope of \( k \) to \( \lambda \) under isotropic loading as shown in Fig. 2b.

![Fig. 2. A general framework of Methane hydrate critical state model by Uchida et al. (2012).](image-url)
behavior under shearing compared to the host soil ($S_h = 0$). The mechanical enhancement appears to increase with hydrate saturation. In addition, the methane hydrate critical state model is highly capable of matching the stress-strain responses of the Nankai hydrate-bearing soil. The determined values of model parameters are summarized in Table 2. These parameters are used for the subsequent sand migration analyses without any variabilities.

![Displacement vectors](image)

**Table 2. Soil model parameters adopted in this study.**

| Notation | Description | Value used |
|----------|-------------|------------|
| $M$      | Critical state stress ratio ($q/p'$) | 1.42 |
| $k$      | Slope of plastic consolidation | 0.26 |
| $k_e$    | Slope of elastic consolidation | 0.013 |
| $\nu$    | Poisson’s ratio | 0.20 |
| $p_{pc}$ | Preconsolidation stress | 5.2 MPa |
| $n$      | Subloading ratio evolution | 2 |
| $p_{cd}$ | Hydrate dependent strength | $97.8(S_h^{0.38})^{-1.5}$ MPa |
| $m$      | Mechanical hydrate saturation | $S_h^{mech} = \exp(-600S_h)$ |
| $E_{so}$ | Hydrate dependent stiffness | $630S_h^{mech}$ MPa |

**3.3 Reservoir response to depressurization**

A 8 MPa of well depressurization is applied with the rate of 4 MPa/day to the homogeneous reservoir (Fig. 1) with the adopted parameters (Tables 1 & 2). Figs. 4a & b show the pore pressure and hydrate saturation profiles at $t = 5$ and 30 days. A well depressurization induces pore pressure reduction, leading to hydrate dissociation. Hydrate dissociation is an endothermic process and the hydrate phase equilibrium pressure is positively correlated to the temperature. Once well pressure is kept constant, a main drive for hydrate dissociation is heat supply. Therefore, hydrate dissociation proceeds more in the lower part of the production zone as it is warmer. This tendency has been reported by many other numerical studies (e.g. Anderson et al., 2011).

Fig. 4c presents the stress ratio, $q/p'$, and the sediment deformation with the scaled arrows. The stress ratio can be used as an indicator of deformation mode such that the increase in $q/p'$ value is the shearing deformation whereas the decrease in $q/p'$ is the volumetric deformation. In this study, the initial value of $q/p'$ is 0.75 and thus $\Delta q/p' < 0$ near the production zone, indicating that the deformation is mostly volumetric. The arrows also imply that the sediments move towards the production zone in a volumetric manner. At the end of 30 days, the maximum displacement is approximately 23 cm (mostly downwards) happening just above the production zone. It is not significant in this study but the sediments away from the production zone can deform in shearing manner, that is, $\Delta q/p' > 0$, due to the effective radial stress reduction and simultaneous effective circumferential stress increase. The shearing deformation may become significant when the initial vertical and horizontal effective stresses are identical and/or when the well is not radially fixed, in other words, an open hole.

![Stress ratio and deformation](image)

**Fig. 4. Reservoir responses in terms of (a) pore pressure; (b) hydrate saturation and (c) stress ratio and deformation.**

**3.4 Sand migration and its variance**

Fig. 5a shows the evolution of the ratio of the hydraulic gradient to the critical gradient in a logarithmic scale at $t = 5$ and 30 days. Due to depressurization and hydrate dissociation, the hydraulic
gradient ratio, $i_w/i_w^{\text{crit}}$, is high near the well and there is a little change in the value with time. In contrast, away from the well, the ratio slightly increases with time with little change in the critical gradient. This is because hydraulic gradient gradually increases away from the well due to permeability increase near the well induced by hydrate dissociation.

Fig. 5b presents the development of deviatoric strain with time. Although the deformation of the sediments is mostly volumetric, the deviatoric strain also develops and it coincides with the area where non-uniform hydrate dissociation occurs. The development of relative differences in sediments’ stiffness and strength, together with the stress re-distribution, causes the hydrate-bearing sediments to deform in shear and this becomes particularly evident after hydrate is gone.

Fig. 5c presents the development of detached solid volume (positive denotes detachment) with time. As described in Eq. (2), solid detachment requires the conditions of both $i_w/i_w^{\text{crit}} > 1$ and $\varepsilon_d > 0$. Therefore, a large amount of solid is detached near the well due to shearing deformation (Fig. 5b) and no detachment away from the well due to $i_w/i_w^{\text{crit}} < 0$ (Fig. 5a).

Fig. 5. Sand migration evolution.

The development of sand migration should depend on the adopted values of the six model parameters (Table 1). In order to assess the effect of each parameter in a simple manner, this study assumes that each parameter is independent, that is, zero covariance among the six parameters. As a result, the variance of the sought-after response value $Y$, which is given by $Y = f(X_1, X_2, \ldots, X_6)$ where $X_i$ are the variables, can be approximated by the following Taylor’s series expansion:

$$\text{var}[Y] = \sum_i \left( \frac{\partial Y}{\partial X_i} \right)^2 \text{var}[X_i]$$

(8)

where $\text{var}[x]$ is the variance of $x$ and in this study $X_i$ are the six parameters. Accordingly, the sensitivity of the overall variance to each parameter, also known as the first-order sensitivity index, $S_i$ (Sobol, 1993), can be quantified as:

$$S_i = \frac{\left( \frac{\partial Y}{\partial X_i} \right)^2 \var{X_i}}{\text{var}[Y]}$$

(9)

For simplicity, this study also assumes that $\partial Y/\partial X_i$ can be obtained by the gradient of $Y$ about one standard deviation, $\sigma_{X_i}$, above and below the mean of $X_i$, $\mu_{X_i}$, in other words, $\partial Y/\partial X_i = (f(\mu_{X_i} + \sigma_{X_i}) - f(\mu_{X_i} - \sigma_{X_i}))/2\sigma_{X_i}$. This is one of the common approaches for probabilistic design in geotechnical community (e.g. Duncan, 2000).

Table 3. Sensitivity of the produced sand to the parameters

| Variables $X_i$ | First-order sensitivity indices $S_i$ |
|-----------------|--------------------------------------|
| $\theta_1$      | 0.0%                                 |
| $\theta_2$      | 1.5%                                 |
| $\theta_3$      | 56.7%                                |
| $\theta_4$      | 24.7%                                |
| $\theta_5$      | 0.0%                                 |
| $i_w^{\text{crit}}$ | 17.1%                                |

Fig. 6. Probabilistic production histories of (a) sand and (b) gas over a period of 30 days.

Table 3 presents the first-order sensitivity indices of the produced sand volume. The values are averaged
over 30 days as \( Y \) (produced sand volume) can be measured at any time. As can be seen, the amount of produced sand volume is mostly (81.4 \%) dominated by the parameters \( \omega_3 \) and \( \omega_4 \), which are the one that determines the increasing effect of hydrate on the critical gradient, Eq. (3), and the one that converts the deviatoric strain to the sand migration potential, Eq. (5), respectively.

The overall variance can be used for probabilistic prediction. Fig. 6a presents the development of volume of produced sand with confidence level of 50 \% and 95 \%. It means that based on the parameters in Table 1 with the coefficient of variation of 25 \%, there is a stated chance that the produced sand volume falls into the shaded region. From Table 3, it is now known that the less variance the parameters \( \omega_3 \) and \( \omega_4 \) have, the more reliable the predicted produced sand volume becomes. For a comparison, Fig. 6b presents the prediction of volume of produced gas. The small width of the prediction range implies that sand migration has little effect on gas production. This does not mean that gas production does not affect sand migration and the study on its effect will be carried out in the future.

4 CONCLUSIONS

This study presents sand migration development in homogeneous gas hydrate reservoir with a limited production zone. The sand migration is found to occur in a greater amount where non-uniform hydrate dissociation develops. Furthermore, through variance-based sensitivity analysis, it is found that the parameters \( \omega_3 \) and \( \omega_4 \) dominantly affect the volume of sand production. In other words, it is important to carefully determine the parameters \( \omega_3 \) and \( \omega_4 \) for an accurate prediction of sand production. Experimental work on the determination of \( \omega_3 \) and \( \omega_4 \) are ongoing.

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