Numerical analyses of dynamic behavior of seabed ground during methane hydrate production

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ABSTRACT

Oceanic methane hydrates are now viewed as energy resource because they contain rich methane. However, they generally exist in relatively shallow and uncemented seabed ground layer, thus large deformation and degradation of seabed sediments may occur during gas production from methane hydrate bearing sediments. Moreover, because they are often found in seismically active regions, including the Nankai Trough area of Japan, there is a risk of large earthquakes during gas production. Seabed sediments damaged by gas production may become trigger of disasters like seabed slides. Furthermore, effects of pore pressure change induced by earthquake on methane hydrate dissociation behavior are also curious problem. In the present study, we have shown a numerical method which can simulate the seismic and chemo-thermo-mechanical coupled behaviors of seabed grounds during gas production, such as phase changes from hydrates to water and gas, temperature changes, ground deformation and the flow of pore fluids. Numerical analyses are performed for the hydrate-bearing sediments at the Daini-Atsumi knoll, Eastern Nankai Trough, Japan, where the world’s first offshore production test of methane hydrates was conducted using a predicted Nankai Trough Earthquake for investigating the earthquake-induced dynamic behavior during gas production. From the results, effects of gas production on mechanical behavior of seabed grounds during earthquake is small for this ground conditions. Small increase of the pore pressure due to methane hydrate dissociation during earthquake results in temporal stability of methane hydrates.

Keywords: methane hydrate, earthquake, depressurization

1 INTRODUCTION

Nowadays, Methane hydrates which are solid crystalline compounds consist of methane and water are viewed as a new energy resource, since large amounts of methane gas can be extracted from the methane hydrates. They are naturally found in permafrost sediments and in deep seabed grounds under high pressure and low temperature conditions.

Since methane hydrates are solid substances, they must be dissociated into methane gas and water in the ground layer. However, as the methane hydrates generally exist in relatively shallow and uncemented seabed ground layer, large deformation of seabed sediments may occur due to methane hydrate dissociation and external force for gas production such as heating and depressurization (Fig. 1.). The sediment degradation induced by the gas production may decrease gas recovery efficiency and damage production wells. Moreover, it may lead to seabed slide at worst. In addition to these problems, since oceanic methane hydrates are often found in seismically active regions, including the Nankai Trough area of Japan and the Storegga area of Norway, there is a risk of large earthquakes during the period of gas production. Seabed sediments damaged by gas production may show unfavorable seismic behaviors such as large oscillation or large acceleration (Fig. 1.), and may become trigger of seabed slides. Furthermore, effects of pore pressure change induced by the earthquake on methane hydrate dissociation behavior are also curious problem.

In the present study, we have shown an outline of a numerical method which can simulate the seismic behaviors of seabed grounds and chemo-thermo-mechanical coupled behaviors during gas production, such as phase changes from hydrates to water and gas, temperature changes, ground deformation and the flow of pore fluids. numerical analyses are performed for the hydrate-bearing sediments at the Daini-Atsumi knoll, Eastern Nankai Trough, Japan, where the world’s first offshore production test of methane hydrates was conducted and is in fault region of Nankai earthquake (Fig. 2.), in order to investigate the earthquake-induced dynamic

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behaviors during gas production.

Fig. 1. Deformation and degradation induced by gas production.

Fig. 2. The world’s first offshore production test site, methane hydrate concentration zone around Japan and fault area of Nankai earthquake.

2 NUMERICAL METHOD

An outline of a chemo-thermo-mechanical coupled dynamic analysis method (Akaki et al. 2016) for calculation of earthquake process during gas production from methane hydrate bearing sediments are shown in this chapter.

2.1 General setting

Hydrate-bearing sediments are composed of four phases, namely, soil particles ($S$), hydrates ($H$), water ($W$) and methane gas ($G$), which are continuously distributed throughout space. For simplicity, we assume that the soil particles and the hydrates move together. The volume fraction $n^\alpha$ is defined as the local ratio of the volume element with respect to the total volume, as follows:

$$n^\alpha = V^\alpha / V,$$

$$\sum_\alpha n^\alpha = 1 \quad (\alpha : S, H, W, G) \quad (1)$$

The volume fraction of voids, $n$, and the volume fraction of the fluid, $n^F$, are given by

$$n = 1 - n^S \cdot n^F = n - n^H \quad (2)$$

In addition, the saturation $s_r$ and the hydrate saturation $s_r^H$ are defined as

$$s_r = n^W / n^F \cdot s_r^H = n^H / n \quad (3)$$

2.2 Stress variables

We use the skeleton stress $\sigma'$ given by following equation as the basic stress variable for the solid phase.

$$\sigma' = \sigma + P^F I \quad (4)$$

$$P^F = s_r P^W + (1 - s_r) P^G \quad (5)$$

$\sigma$ is the total stress tensor and $P^F$ is the average pore pressure.

2.3 Conservation laws

Conservation laws are defined for each phases, and some equations used in our analysis method are derived from them. The volume fraction of the voids and the methane hydrates are calculated by the mass conservation for soil particles and methane hydrates.

$$n^S + n^S \nabla \cdot V^SH = 0 \quad (6)$$

$$n^H + n^H \nabla \cdot V^SH = \frac{m^H}{\rho^H} \quad (7)$$

where $V^SH$ is the velocity of soil skeleton consist of soil particles and methane hydrates. Continuity equation for water and methane are given by

$$s_r \nabla \cdot V^W + \dot{s}_r n^F + \nabla \cdot V^W = s_r \frac{m^H}{\rho^H} + \frac{m^W}{\rho^W} \quad (8)$$

$$\begin{align*}
(1 - s_r) \nabla \cdot V^{SH} - \dot{s}_r n^F + \nabla \cdot V^G + (1 - s_r) n^F \frac{\dot{m}^G}{\rho^G} \\
= \frac{\dot{m}^H}{\rho^H} + \frac{\dot{m}^W}{\rho^W}
\end{align*} \quad (9)$$

where $V^W$ and $V^G$ are water and gas average relative velocity to solid phase, $\rho^W$, $\rho^G$ and $\rho^H$ are densities for water, methane gas and methane hydrate. $V^W$ and $V^G$ are given by the Darcy type equations. $m^W$, $m^G$ and $m^H$ are the water, methane and methane hydrate mass-generation rate per unit volume.

Movement of soil skeleton can be given by solving the conservation of momentum for mixture.

$$\rho \dot{\nabla} = \nabla \cdot \sigma^T + \rho b \quad (10)$$

where $\rho$ is the density for soil mixture. The conservation of energy is as follows;
\[(\rho c^\alpha)^M \dot{\theta} + (\rho^W c^W V^W + \rho^G c^G V^G) \cdot \nabla \theta = \sigma^T : D^{vp} + \nabla \cdot (\lambda^M \nabla \theta) + Q_{\text{diss}}^H \] (11)

\[
(\rho c^\alpha)^M = \sum_{\alpha} n^\alpha \rho^\alpha c^\alpha.
\]

\[
\lambda^M = \sum_{\alpha} \kappa^\alpha \lambda^\alpha.
\]

where \(\theta\) is the temperature, \(c^\alpha\) and \(\lambda^\alpha\) are the specific heat and the coefficients of thermal conductivity for each phase, \(D^{vp}\) is the viscoplastic stretching tensor, \(Q_{\text{diss}}^H\) is heat generation rate per unit volume induced by methane hydrate dissociation. The acceleration of soil skeleton is considered for calculation of earthquake process.

2.3 Constitutive equations

We introduced the hydrate saturation dependency on the stress-strain behavior to a cyclic elasto-viscoplastic model based on overstress type viscoplastic theory with the nonlinear kinematic hardening rules and the structural degradation for solid skeleton (Kimoto et al. 2013). The elastic behavior is given by a generalized Hooke type of law. The shear modulus, which is important for seismic response analysis, decreases with accumulation of viscoplastic shear strain. We assumed the ideal gas for the gas phase and van Genuchten model is used for soil-water characteristic curve. Kim-Bishnoi equation (Kim et al. 1987) is used for methane hydrate dissociation rate which determine mass generation rate per unit volume, \(m^H\), \(m^G\) and \(m^M\).

3 SIMULATION CONDITIONS

Model setting for seabed ground with hydrate-bearing layer at the Daini-Atsumi knoll, Eastern Nankai Trough, Japan is explained in this section. The finite element mesh and the boundary conditions used in the simulations are shown in Fig. 3. A horizontally layered ground under two-dimensional plane strain conditions is assumed. Sediments are divided into 6 layers and the layer 5 (L5) is a methane hydrate-bearing layer. The hydrate-bearing sediment layer has a thickness of 60 m 270 m bellow the seabed. Methane hydrates are dissociated by depressurization same as the world’s first offshore production test. The depressurization source is placed at the upper side of the methane hydrate-bearing layer. The pore water pressure and the gas pressure at the depressurization source are depressurized from 12.5 MPa to 6.5 MPa during a period of about 25 hours, as shown in Fig. 4. A gas production process lasting 50 days was firstly simulated, and then a dynamic analysis for the earthquake process was conducted (Case 2). A dynamic analysis without the gas production process (Case 1) was also conducted for comparison. The input ground motion is illustrated in Fig. 5., which is the expected earthquake motion at the site where the first methane hydrate production test was conducted at the Daini-Atsumi knoll, Eastern Nankai Trough, Japan using the EMPR earthquake simulation method by Sugito et al. (2000). The magnitude of the hypothetical earthquake is 9.0 and the epicenter is off the coast of the Kii Peninsula. The maximum acceleration is 2.73 m/s\(^2\) and the duration time is 320.0 sec.

The initial methane hydrate saturation in the hydrate-bearing layer is 40%. Material parameters for soil skeletons for layer 1,2,3,4,6 are determined on undrained triaxial tests and constant rate of strain rate consolidation test conducted for low liquidity clay samples recovered from the area of the first Japanese offshore production test at the Eastern Nankai Trough (Nishio et al. 2013a,b, Nishio et al. 2014). For layer 5, we determined the material parameters based on drained triaxial compression tests using samples obtained from hydrate-bearing sediments recovered by pressure coring at the first offshore production test site (Yoneda et al. 2015). The simulation results of the drained triaxial tests for the methane hydrate-bearing layer are shown in Fig. 6. Simulation results for \(x^H_s = 40.0\%\) is correspond to material parameters used in this study.

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Fig. 3. Finite element mesh and boundary conditions (Akaki et al. 2016).
3 SIMULATION RESULTS

Distributions of displacements and the degree of remaining methane hydrates before earthquake (= after 50 days gas production) are shown in Fig. 7. Settlements due to gas production occur in seabed sediments. Maximum displacement is found in Layer 4 above the methane hydrate bearing sediments. Methane hydrates dissociate around the depressurization source. Earthquake occur under these ground conditions different from initial state before gas production.

Shear strain – shear stress ratio relations on Elements 1-4 for Case 2 are displayed in Fig. 8. White circles in the Fig. 8 show initiation of the earthquake. Maximum shear stress ratio during the earthquake for elements 1-4 are about 0.1% and shear strain amplitude for elements 1-4 for Case 2 are displayed in Fig. 8. White circles in the Fig. 8 show initiation of the earthquake. Maximum accelerations for Case 2 are smaller than Case 1, and the increasing distance from Node 1. The maximum accelerations and velocity on seafloor are displayed in Fig. 5. Input ground motion (Akaki et al. 2016).

The increase in the average pore pressure during earthquake in elements are plotted in Fig. 12(b). The open circles are the elements with hydrate dissociation during the earthquake, and the closed circles are the elements without hydrate dissociation during the earthquake. The black triangles are the elements without hydrate dissociation adjacent to the elements with hydrate dissociation during the earthquake.

The increase in the average pore pressure during earthquake in elements are plotted in Fig. 12(b). The average pore pressure increases mainly in the elements in which methane hydrates dissociated during earthquake (open circles). Therefore, it become clearer that the increase of the average pore pressure is due to generation of methane gas induced by methane hydrate dissociation.

4 CONCLUSIONS

In the present study, we have presented an outline of the numerical method which can simulate the seismic behaviors of seabed grounds including chemo-thermo-mechanical coupled behaviors during gas production from methane hydrate-bearing sediments. Numerical analyses are performed under two-dimensional plane strain conditions for the hydrate-bearing sediments at the Daini-Atsumi knoll, Eastern Nankai Trough, Japan. From the results following conclusions are obtained.

1. The maximum shear stress ratio during earthquake
is about 0.10 and the shear strain amplitude for elements 1-4 is about 0.1% at most.

2. The increase of the maximum acceleration due to gas production is around 0.05 m/s², and the decrease of the maximum velocity due to gas production is about 0.05 m/s.

3. The maximum velocity increases due to gas production from 100 m to 0 m in depth. The increase is about 10%.

4. From the conclusions 1, 2 and 3, effects of gas production on mechanical behavior of seabed grounds during earthquake would be small, and it would not lead to severe damage on the seabed sediments and the production well under the studied conditions.

5. A few kPa of increase of the average pore pressure due to the methane hydrate dissociation is found during earthquake. The increase of the average pore pressure results in temporal stability of methane hydrates.

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Fig. 7. Distribution of displacements and distribution of degree of remaining methane hydrates after 50 days gas production.

Fig. 8. Shear strain – shear stress ratio relations.

Fig. 9. Distribution of maximum acceleration and velocity on seafloor.

Fig. 10. Distribution of maximum acceleration and velocity in depth at center of seabed sediments.

Fig. 11. Time profiles of methane hydrate dissociation rate per unit volume and average pore pressure during earthquake in methane hydrate-bearing layer.
Fig. 12. Effects of methane hydrate dissociation on increase in average pore pressure during earthquake (Modified from Akaki et al. 2016).

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