Numerical Simulation of the Subsurface Ground Deformations due to Methane Hydrate Dissociation

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1. Introduction

Methane hydrates are presently viewed as a potential energy resource for the 21st century because a large amount of methane gas is trapped in hydrate reservoirs (Research Consortium for Methane Hydrate Resources in Japan, Website 2006). There are several problems to be solved during the production of natural gas from methane hydrate. These mainly relate to the 1) exploration of high quality deposits containing methane hydrate, 2) investigation of methods for producing of gas, and 3) study of effects of gas production on the environment. The third one includes the ground deformation due to the extraction of methane hydrate and the leakage of gas. When we produce gas from the marine sediments, extensive subsurface deformations may lead to a sea bed slide, while the leakage of gas affects

the marine water environment and subsequently contributes to global warming. In the case of Nankai Trough around Japan, it is found that methane hydrate is buried under the sea bottom at a water depth of about 1000m. Several production schemes have been proposed to extract the gas from hydrates, namely, heating, depressurization, and inhibitor injection methods. Since there are many uncertainties in the production process, especially related to the subsurface deformations caused by dissociation, numerical studies are useful to predict thermo-hydro-mechanical behavior as well as to evaluate the production methods. In order to accurately predict the behavior of a seabed subsurface, due to the dissociation of natural gas hydrates, it is necessary to develop a powerful numerical simulator which is capable of considering ground deformation, water and gas flow, phase change from solid to fluids, and heat transfer.

Another aspect of MH is also related to the global warming problem. The National Academy of Sciences (2004) has been reported that MH naturally

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dissolves into gas and water without any artificial actions and it accelerates global warming process. This indicates the importance of the scientific study of dissociation process.

In the dissociation process, the generated gas pressure cannot be disregarded, and hence, the soil behavior in an unsaturated state becomes important in predicting the ground deformation. When modeling the mechanical behavior of an unsaturated soil, it is necessary to choose appropriate stress variables since they control its mechanical behavior. In the present study, the average skeleton stress, which is determined from the difference between the total stress and the average pore fluid pressure, is used for the stress variable in the constitutive model. Furthermore, the effect of suction is expressed in the constitutive equation. In addition, the strength of the soil strongly depends on the saturation of the hydrates in the void, since hydrates work as bonds between soil particles.

2. Simulation method

2.1 Risk map and I-Chart

Geomaterials in general fall into the category of multiphase materials. They are basically composed of soil particles, water, and air. The behavior of multiphase materials can be described within the framework of a macroscopic continuum mechanical approach through the use of the theory of porous

media (Boer 1998). The theory is considered to be a generalization of Biot's two-phase mixture theory for saturated soil (Biot 1956). Proceeding from the general geometrically non-linear formulation, the governing balance relations for multiphase materials can be obtained (e.g., Boer 1998; Ehlers 2003). Mass conservation laws for the gas phase as well as for the liquid phase are considered in those analyses. In the field of geotechnics, air pressure is assumed to be zero in many research works (e.g., Sheng et al. 2003), since geomaterials usually exist in an unsaturated state near the surface of the ground. Considering hydrate dissociation, however, we have to deal with the high level of gas pressure that exists deep in the ground; this means that the mass balance for both phases must be considered. Oka et al. (2006) proposed an air-water-soil coupled finite element model in which the skeleton stress is used as a stress variable, the suction effect is introduced in the constitutive equation for soil, and the simulated compression behavior for unsaturated soils is under impermeable conditions for both water and gas flow. Furthermore, the conservation of energy is required when there is a considerable change in temperature during the deformation process. Vardoulakis (2002) showed that the temperature of saturated clay rises with plastic deformation. Oka et al. (2004, 2005) numerically simulated the thermal consolidation process. Since hydrate dissociation is an endothermic reaction, heat transfer plays an important role in both gas production and ground deformation.

2.2 Volume fraction

The material to be modelled is composed of four phases, namely, solid (S), water (W), and gas (G), which are continuously distributed throughout space, and hydrates (H). For simplicity, we assume that hydrates (H) move with the solid phase before dissociation. Total volume V is obtained from the sum of the partial volumes of the constituents, namely,

$$\sum_{\alpha} V^{\alpha} = V \ (\alpha = S, W, G, H) \tag{1}$$

Volume fraction n^{α} is defined as the local ratio of the volume element with respect to the total volume, namely,

$$n^{\alpha} = \frac{V^{\alpha}}{V} \tag{2}$$

$$\sum_{\alpha} n^{\alpha} = 1 \ (\alpha = S, W, G, H) \tag{3}$$

2.3 Skeleton stress

In the theory of porous media, the concept of the effective stress tensor is related to the deformation of the soil skeleton and plays an important role. The effective stress needs to be redefined if the fluid is made of compressible materials. In the present study, skeleton stress tensor σ'_{ij} is defined and then used for the stress variable in the constitutive relation for the soil skeleton. Total stress tensor σ'_{ij} is obtained from the sum of the partial stress values, σ^{α}_{ij}. The skeleton stress σ'_{ij} which is used as the stress variable in the constitutive relation for the soil skeleton is given by

$$\sigma'_{ij} = \sigma_{ij} - P^{F} \delta_{ij} \tag{4}$$

where P^{F} is the average pressure of the fluids surrounding the solid skeleton (Schrefler 1996) given by

$$P^{F} = s_{r} P^{w} + (1 - s_{r}) P^{G} \tag{5}$$

2.4 Conservation of mass

The conservation of mass for the solid, water and gas phases, $\beta (= S, W, G)$, is given in the following equation:

$$\frac{\partial}{\partial t} (\rho^{\beta} n^{\beta}) = -q^{\beta}_{Mi, i} + \dot{m}^{\beta} \tag{6}$$

in which ρ^{β} is the material density, q^{β}_{Mi} is the flux vector of the fluid, and $\dot{m}^{\beta}$ is the mass rate of change per unit volume generated by dissociation. The flow of water and gas are assumed to be controlled by a Darcy type of law.

Assuming that spatial gradients of volume fraction and density are negligible and the soil particle is incompressible, $\dot{\rho}^{s} = 0$. The mass conservation law for the solid phase, in Eq. (6) becomes

$$-\dot{n} + (1-n) \dot{v}^{s}_{i, i} = 0 \tag{7}$$

For the methane hydrate phase, the hydrate

decomposes to form methane gas and water due to an increase in temperature and a decrease in pressure. Therefore, the mass of the hydrate decreases due to its dissociation following the chemical reaction equation, Eq. (6) in Section 2.4. Since rehydration of the methane gas is not considered in the present paper, the dissociation process is not reversible.

2.5 Conservation of momentum

The sum of the momentum balance equation for each phase leads to

$$\sigma'_{ji,j} + \rho^E \bar{F}_i = 0, \rho^E = \sum_\alpha n^\alpha \rho^\alpha \ (\alpha = S, W, G) \qquad (8)$$

The rate type of conservation for the momentum is

given by

$$\dot{S}^t_{ji,j} = 0 \qquad (9)$$

in which changes in the material density are ignored. In the above, $\dot{S}^t_{ij}$ is the total nominal stress rate tensor.

2.6 Conservation of energy

The following energy conservation equation is applied in order to consider the heat conductivity and the heat sink rate associated with hydrate dissociation:

$$(\rho c)^E \dot{\theta} = D^{vp}_{ij} \sigma'_{ij} - h_{i,i} + Q^H, (\rho c)^E = \sum n^\alpha \rho^\alpha C^\alpha$$
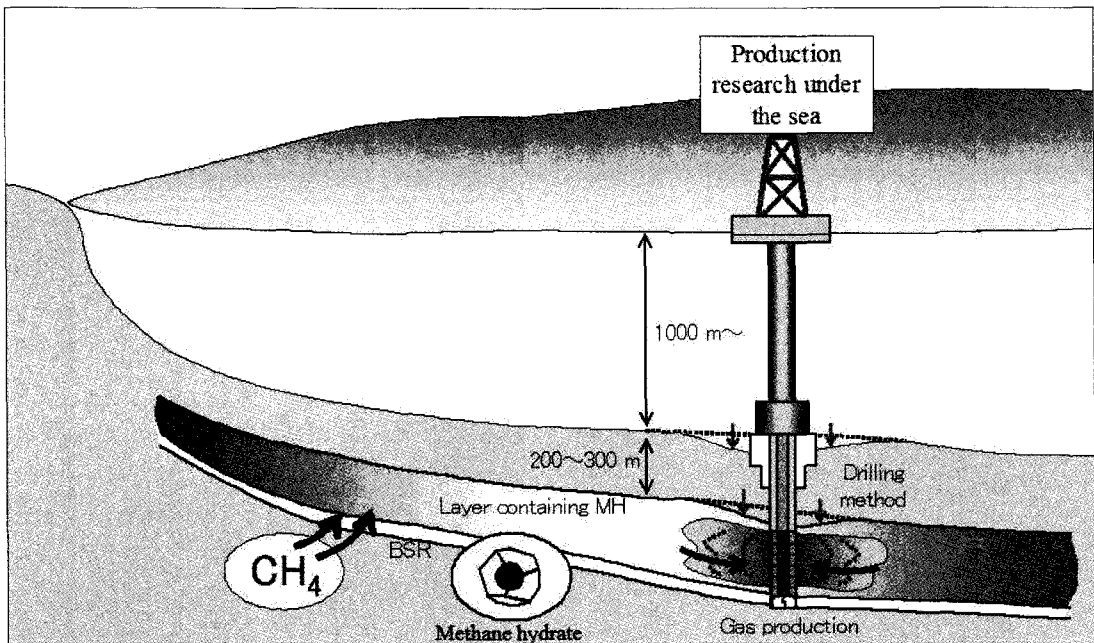$$(\alpha = S, W, G, H) \qquad (10)$$

Figure 1. Production of natural gas from methane hydrate under the sea

where C^α is the specific heat, $\theta(K)$ is the temperature for all the phases, D_{ij}^{vp} is the viscoplastic stretching tensor, h_i is heat flux vector, and Q^H is the dissociation heat rate per unit volume due to hydrate dissociation.

2.7 Soil-water characteristic curve

The relation between suction and saturation is given in the following equation proposed by van Genuchten (1980):

$$S_{re} = \{1+(\alpha P^C)^n\}^{-m} \tag{11}$$

in which α, m, and n are material parameters, and the relation m = 1-1/n is assumed. $P^C(=P^G-P^W)$ is the suction and S_{re} is the effective saturation.

3. Dissociation of hydrates

If the conditions for pore pressure and temperature shift to the unstable region given in the following equation, as schematically shown in Figure 2, gas hydrates dissociate into water and gas with the reaction expressed in Equation (13). The average pressure of the fluids, P^F, is regarded as pore pressure P in the analysis.

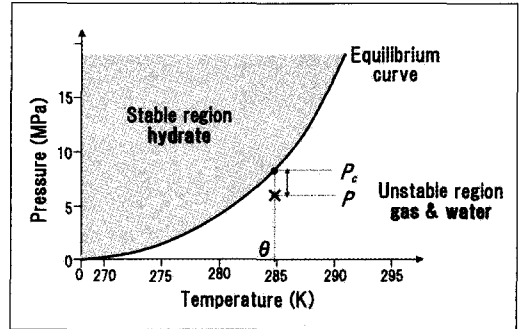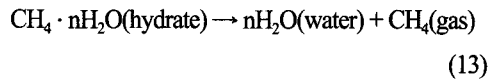$$P \leq c \exp\left[a - \frac{b}{T}\right] \text{ (Unstable region)} \tag{12}$$

Figure 2. Equilibrium curve for methane hydrates

$$CH_4 \cdot nH_2O(\text{hydrate}) \rightarrow nH_2O(\text{water}) + CH_4(\text{gas}) \tag{13}$$

where a, b, and c are material parameters. n is a hydrate number and is assumed to be equal to 5.75. Dissociation ratio N^H(kmol/s) is given by the following Kim-Bishnoi equation (Kim et al. 1987):

$$N^H = -0.585 \times 10^{10} \times \exp^{-\frac{9400}{\theta}} (P^e-P) N^{H_0 \frac{1}{3}} N^{H \frac{2}{3}} \tag{14}$$

in which N^H(kmol) is the moles of hydrates in volume $V(m^3)$, N^{H_0}(kmol) is the moles of hydrates at the initial state, P(kPa) is the average pore pressure, and P^e is an equilibrium pressure at temperature θ(K). When dissociation occurs, the dissociation ratio is negative, i.e. $N^H \langle 0$. Mass increasing ratios (t/sec/m³) for hydrates, water, and the gas phase, required in the mass conservation law, are obtained from the above equations.

4. Constitutive model for soil

Natural hydrates exist between soil particles and are considered to have a bonding effect which increases the solid phase strength. From this point of view, we introduced the effect of hydrate saturation in an elasto-viscoplastic model (Kimoto et al. 2004) by means of the shrinkage or the expansion of the OC boundary surface and the static yield surface.

An elasto-viscoplastic model of the overstress type viscoplasticity with soil structure degradation for saturated soils has been extended to unsaturated soils using the skeleton stress and the newly introduced suction effect within the constitutive model (Oka et al. 2006). Furthermore, the temperature dependency of the viscoplastic property of soils is introduced in the model based on the work (by Yashima et al. 1998).

5. Simulation results

Weak forms of Equations, that is, Conservation of mass for water and gas, conservation of momentum, and Conservation of energy are discretized in space and solved by the finite element method. For finite element method, an updated Lagrangian method with the objective Jaumann rate of Cauchy stress is used. The unknown variables are nodal velocity, pore water pressure, pore gas pressure, and temperature. In the finite element formulation, an eight-node quadrilateral element with a reduced Gaussian integration is used for the displacement, and four corner nodes are used

Table 1. Initial conditions

Porosity	n_0	0.47
Water saturation	S_{r0}	1.0
MH saturation in the void	S_{r0}^H	0.643
Temperature	θ_0	282 (K)
Vertical effective stress	σ'_{v0}	1150 (kPa)
Earth pressure at rest	K_0	1.0
Pore water pressure	P^W_0	11000 (kPa)

Table 2. Material parameters of the soil

| Initial void ratio	e	0.887
Initial mean effective stress	σ'_{m0}	1150 (kPa)
Initial shear elastic modulus	G_0	53800 (kPa)
Viscoplastic parameter	C_0	3.5×10^{-9} (1/s)
Viscoplastic parameter	m'	23
Stress ratio at failure	M'_m	1.09
Compression yield stress	σ'_{mbi}	1150 (kPa)
Compression index	λ	0.169
Swelling idex	κ	0.017
Structural parameter	σ'_{maf}	1150 (kPa)
Structural parameter	β	0
Parameter for MH effect	S^H_{ri}	0.65
Parameter for MH effect	n_m	0.4
Parameter for MH effect	n_d	1.5
Parameter for suction effect	P^C_i	100 (kPa)
Parameter for suction effect	S_I	0.2
Parameter for suction effect	s_d	0.25
Thermo-viscoplastic parameter	α	0.15
Permeability for water	k^W	1.0×10^{-9} (m/s)
Permeability for gas	k^G	1.0×10^{-8} (m/s)
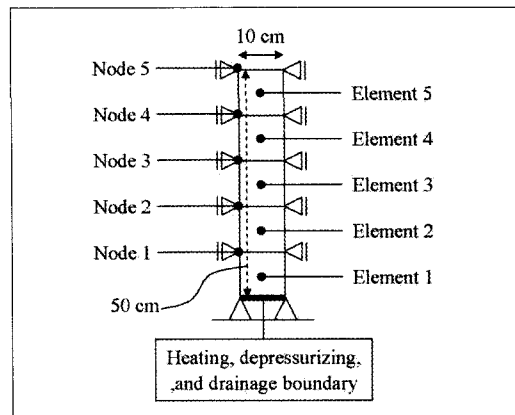
Figure 3. Number of elements and nodes

Table 3. Material parameters of the soil-water
characteristic curve

Maximum saturation	S_{max}	1
Minimum saturation	S_{min}	0
van Genuchten parameter	a	0.005 (1/kPa)
van Genuchten parameter	n	10

for the pore pressures and the temperature. The
backward finite difference method is used for the time
discretization. We have simulated the dissociation
process by heating and depressurizing a seabed
subsurface. The finite element meshes are shown in
Figure 3. The seabed ground is modeled at a water
depth of 1100 m and at ground depth of 200 m from
the bottom of the sea. All the elements are initially in
a stable state, that is, they have a pressure level of 11
MPa and a temperature of 282 K. The initial
conditions are summarized in Table 1. The initial
porosity is set to be 0.47 and the initial saturation of
the methane hydrate (MH) in the void is set to be
0.643, that is, the initial volume fraction of MH is
about 0.3. The ground is assumed to be saturated at
the initial state. The bottom edge is heated to 303 K or
depressurized to 7 MPa in order to promote
dissociation, and water and gas flow out from the
bottom edge. The material parameters of the soil are
listed in Table 2. These are basically determined from
the results of triaxial tests conducted on samples
obtained from the field research conducted along the
Nankai Trough (Japan National Oil Corporation,
2000). The maximum water permeability is assumed
to be 1.0×10^{-9} m/s and the maximum gas permeability
is assumed to be 1.0×10^{-8} m/s. Notice that the gas
permeability is equal to zero before dissociation,

whereas it takes a constant value and gas can flow out
through the saturated soils after dissociation. The
material parameters that describe the soil-water
characteristic curve are listed in Table 3.

5.1 Heating method

In simulations of the heating method, the bottom of
the specimen is heated from 282 K to 303 K in 20000
sec (=5.6 hours). The results are shown in Figures 4
(a)-(f). Figure 4 (a) shows the changes in the number
of moles of the hydrates for each element.
Dissociation progresses from the bottom to the top
elements, and it takes longer for the top element to
dissociate than the bottom element, that is, about 2
hours for Element 1 and about 70 hours for Element
5. Figure 4 (b) shows the changes in temperature. The
temperature in the elements increases due to the heat
supply from the bottom. It is then seen that Element 1
begins to dissociate at about 2 hours when the
temperature reaches 286 K, namely, a value on the
dissociation equilibrium curve. The temperature
remains constant in Element 1 during the dissociation,
which means that all of the heat is consumed towards
dissociation. On the other hand, the temperature in the
other elements decreases during the dissociation of
Element 1 due to the heat sink arising from the
dissociation process. After the dissociation,
temperature increases again in all the elements. Next,
methane hydrates of Element 2 start to dissociate at
about 10 hours when the temperature in Element 2
reaches 286 K as shown in Figure 4 (b). The value of

Numerical Simulation of the Subsurface Ground Deformations due to Methane Hydrate Dissociation
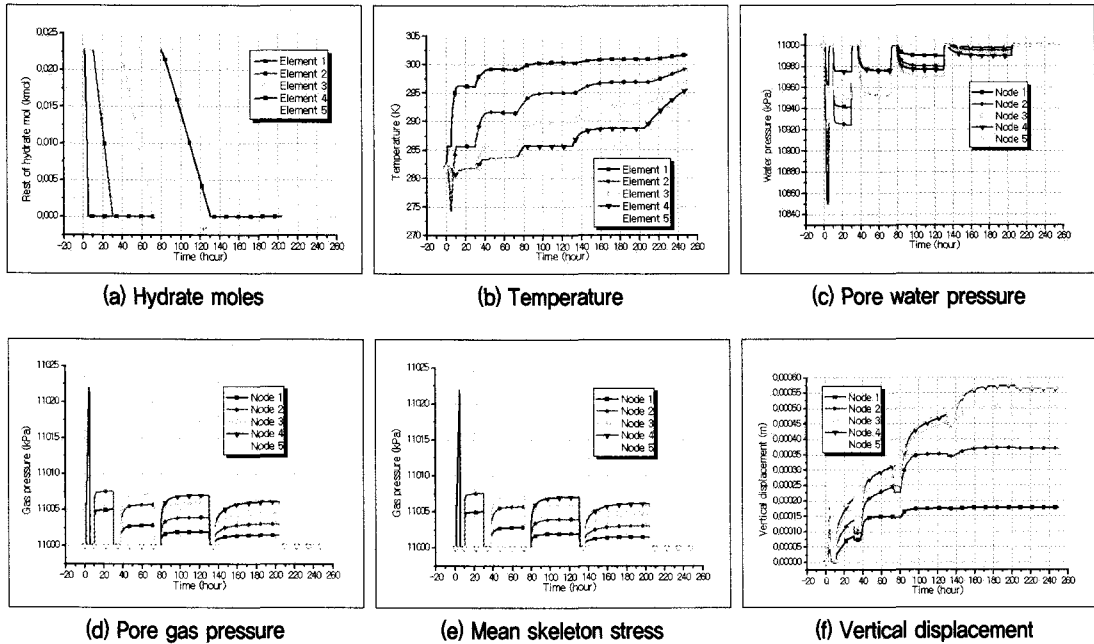
(a) Hydrate moles

(b) Temperature

(c) Pore water pressure

(d) Pore gas pressure

(e) Mean skeleton stress

(f) Vertical displacement

Figure 4. (a)–(f) Simulation results for the heating method

(a) Hydrate moles

(b) Temperature

(c) Pore water pressure

(d) Pore gas pressure

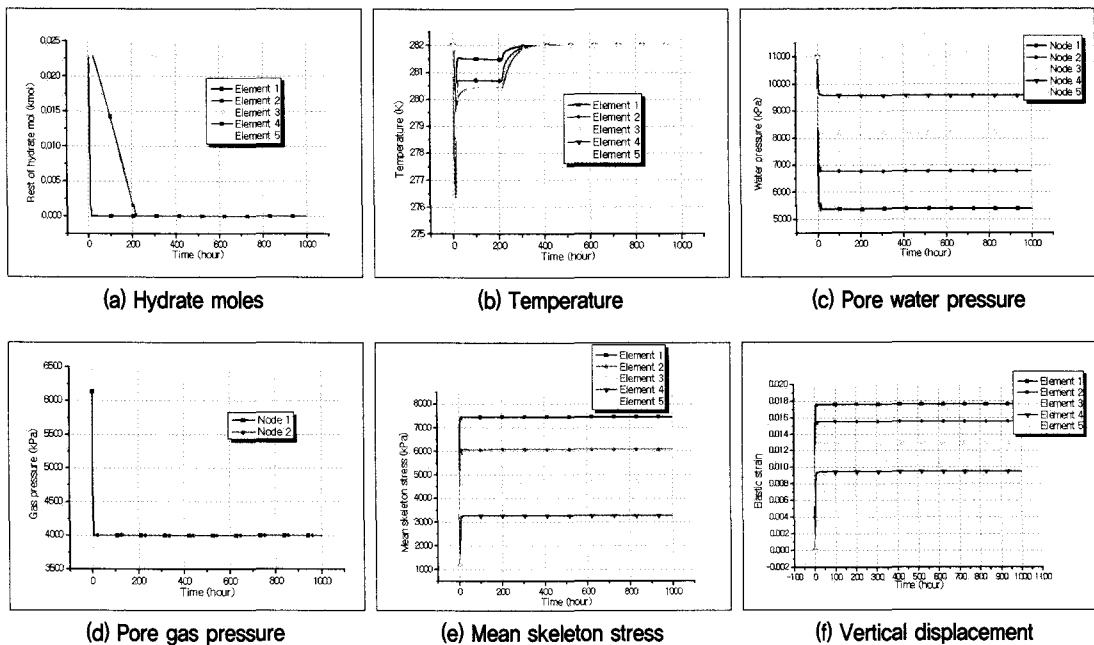(e) Mean skeleton stress

(f) Vertical displacement

Figure 5. (a)–(f) Simulation results for the depressurization method

temperature remains almost constant in all of the other elements during the dissociation of Element 2. Similar behaviors can be seen during the subsequent dissociation of hydrates of Elements 3, 4, and 5.

Figures 4 (c) and (d) show the generated water pressure and gas pressure at the nodes. The water pressure suddenly decreases and the gas pressure increases when the MH of Element 1 begins to dissociate. Since the volume rate of the generated water from the hydrates is about 0.8, the water pressure decreases and the water flows into the specimen from the bottom boundary. In contrast, the volume rate of the generated gas from the hydrates is about 1.5 under a pore pressure of 11 MPa, and gas pressure is generated at each node during the dissociation. The maximum suction is less than 200 kPa, and the value of saturation remains mostly at 1.0 during the simulation. This behavior strongly depends on the soil-water characteristic curve. As such, the average pore pressure decreases, which results in an increase in the mean skeleton stress. The vertical displacements are shown in Figure 4 (f). The displacement at the top, after the dissociation of all the elements, is about 0.56 mm, that is, 0.11 % of the average vertical strain. The elastic strain almost completely recovers, whereas the viscoplastic strain does not. This is due to structural degradation with hydrate dissociation and thermal softening.

5.2 Depressurization method

In the depressurization method, the pore pressure at the bottom is depressurized from 11 MPa to 4 MPa in 18000 sec (=5 hours). The results are shown in Figures 5 (a)-(f). In this case, only the MH in Elements 1 and 2 dissociate, while the one in others do not (Figure 5 (a)). This is because the pore water pressure would never be small enough to be in the unstable regions of Elements 3, 4, and 5 due to the boundary conditions indicated in Figure 5 (c). The temperature remains constant during dissociation, as shown in Figure 5 (b). Figure 5 (d) shows the changes in pore gas pressure and it is seen that the pressure increases to values larger than 6000 kPa when the MH in Element 1 dissociates. After the dissociation, about 47 mm of the vertical displacement, that is, 9.4 % of the average vertical strain, remains (Figure 5 (f)). The skeleton stress increases due to depressurization itself, which results in large deformations with respect to viscoplastic and elastic strains, as shown in Figures 5 (f).

We can thus conclude from the simulations that considerable deformations may occur in the dissociation process due to changes in pore pressure, especially in the case of the depressurization method, and that structural changes in the solid phase promote large deformations.

6. Conclusion

We have developed a chemo-thermo mechanically coupled simulation method to predict ground stability during hydrate dissociation, and have simulated the

Numerical Simulation of the Subsurface Ground Deformations due to Methane Hydrate Dissociation

behavior of soil during the dissociation process in a seabed subsurface by the heating and depressurizing methods. From the simulation results, the ground deformation due to the production of pore fluids, changes in the skeleton stresses, and structural changes in the soil structure arising from the loss of hydrate bonding and thermal softening, can all be predicted. Larger ground settlements are predicted in the depressurization method than the ones in the heating method. In future studies, the saturation dependencies of permeability and temperature have to be introduced in the simulation. In addition, two dimensional analyses have to be carried out. Finally, the numerical simulations need to be verified against experimental results, for instance from the consolidation tests associated with the dissociation.

References

1. Biot, M.A. "Theory of propagation of elastic waves in a fluid saturated porous solid", I : Low frequency range, Int. J. Acoust. Soc. Am., 28, p. 168-178, 1956.
2. Boer, R.D. "Theory of porous media-past and present", Z. Angew. Math. Tech, 78 (7), p. 441-466, 1998.
3. Ehlers, W. "Continuum and numerical simulation of porous materials in science and technology", Modeling and mechanics of granular and porous materials, chapter 9, G. Capriz, V.N. Ghionna, P. Giovine, eds, Birkhauser, 2003.
4. Japan National Oil Corporation, Survey Report of 1999-2000 MITI Exploratory Test Wells "Nankai Trough," 2000 (in Japanese).
5. Kim, H.C., Bishnoi, P.R., Heidemann, R.A. and Rizvi, S.S.H. "Kinetics of methane hydrate decomposition", Chemical Engineering Science, 42 (7), p. 1645-1653, 1987.
6. Kimoto S., Oka, F. and Higo, Y. "Strain localization analysis of elasto-viscoplastic soil considering structural degradation", Comput. Methods Appl. Mech. Engrg., 193, p. 2854-2866, 2004.
7. Kimoto, S., Oka, F., Fushita, T. and Fujiwaki, M. "A Chemo-Thermo-Mechanically Coupled Numerical Simulation of the Ground Deformation due to Methane Hydrate Dissociation", Computers and Geotechnics, 2007 (to appear).
8. National Academy of Science, "Charting the future of methane hydrate research in the United States", http://www.nap.edu/catalog/11094.html, 2004.
9. Research Consortium for Methane Hydrate Resources in Japan, http://www.mh21japan.gr.jp/english/index.html.
10. Oka, F., Kimoto, S., Kim, Y.-S., Takada, N. and Higo, Y., "A finite element analysis of the thermo-hydro-mechanically coupled problem of cohesive deposit using a thermo-elasto-viscoplastic model", Poromechanics-Biot-centennial, Proc. 3rd Biot Conference on Poromechanics, Y.N. Abousleiman, A.H-D. Cheng, F-J. Ulm editors, Balkema, p. 383-388, 2005.
11. Oka, F., Kodaka, T., Kimoto, S., Kim, Y.-S and

Yamasaki, N., "An Elasto-viscoplastic Model and Multiphase Coupled FE Analysis for Unsaturated Soil", Proc. 4th Int. Conf. on Unsaturated Soils, Apr. 2-6 2006, Carefree, Arizona, Geotechnical Special Publication, No. 147, ASCE, 2, p. 2039-2050, 2006.

12. Sheng, D., Sloan, W., Gens, A. and Smith, D.W. "Finite element formulation and algorithms for unsaturated soils", Part Ⅰ: Theory. Int. J. Numer. Anal. Meth. Geomech., 27, p. 745-765, 2003.

13. Schrefler, B.A. and Gawin, D. "The effective stress principle: incremental or finite form", Int. J. Numer. Anal. Meth. Geomech., 20 (11), p. 785-814, 1996.

14. van Genuchten, M. Th. "A closed-form equation for predicting the hydraulic conductivity of unsaturated soils." Soil Sci. Soc. Am. J., 44, p. 892-899, 1980.

15. Vardoulakis, I. "Dynamic thermo-poro-mechanical analysis of catastrophic landslides", Geotechnique, 52 (3), p. 157-171, 2002.

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- 주요 수상경력은 일본지반공학회 젊은연구자상(1974), 일본지반공학회 장려상(1980), 일본 지반공학회 논문상 (1986), 일본 토목학회 논문상(1993), ICMAG의 Award for Significant Paper(1997), 일본지반공학회 공로상(1999) 등
- 주요 저서는 지반의 탄점소성 구성식, Mechanics of Granular Materials, 수치해석입문, 지반 액상화의 과학, 토질역학, 토질역학 연습 등