Prediction of stress and strain for the seabed and production well during methane hydrate exploitation in turbidite reservoir

Prediction des contraintes et des déformations pour le fond de la mer et pour le puits pendant l'exploitation d'hydrates de méthane dans un réservoir de turbidite

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ABSTRACT: During MH production, there are concerns about the settlement of the seabed and the possibility that negative friction will occur along production well due to change in effective stress induced by water movement due to depressurization, dissociation of MH, methane gas generation and thermal change, which are all inter-connected. The authors have developed a multi phase coupled simulator using finite element method named COTHMA. Stresses and deformation of methane hydrate vicinity production well and the deep seabed ground were predicted which simulating NANKAI trough where is planned as Japan's first offshore production test area.

RÉSUMÉ : Pendant la production de gaz d'hydrate de méthane, il peut y avoir des phénomènes de tassement du fond marin et de frottement négatif autour du puits. Ces problématiques sont dues à des changements de la contrainte effective induits par un ensemble de phénomènes couplés : écoulements d'eau dus à la dépressurisation, dissociation des hydrates de méthane, génération de méthane et changements thermiques. Les auteurs ont développé un outil de simulation numérique multiphasique par éléments finis, nommé COTHMA. Les contraintes et les déformations au voisinage du puit de production et du fond marin en profondeur ont été simulées dans le cadre du site de NANKAI qui est prévu pour être le premier site de test de production off-shore du Japon.

KEYWORDS: methane hydrate, effective stress, deformation, finite element, multi phase

1 INTRODUCTION

Recent investigations have indicated that methane hydrate (MH) could become a potential future energy resource. In the MH extraction project, a well is drilled into the sea floor from a marine platform. Then, fluids in the well are either heated or depressurized to induce MH dissociation and the dissolution of methane gas is collected in-situ. During MH production, there are concerns about the settlement of the seabed and the possibility that negative friction will occur along production well due to change in effective stress induced by water movement due to depressurization, dissociation of MH, methane gas generation and thermal change, which are all inter-connected. The authors have developed a multi phase coupled simulator using finite element method named COTHMA(Coupled thermo-hydro-mechanical analysis with dissociation and formation of methane hydrate in deformation of multiphase porous media). Reliability of the simulator is being established by predicting experimental model tests and performing parametric study (Sakamoto, 2010). In this paper, predict stresses and deformation of methane hydrate vicinity production well and the deep seabed ground which simulating NANKAI trough where is planned as Japan's first offshore production test area.

In this study, production well was constructed in the simple geological model of NANKAI trough for evaluating the strain of the seabed and stress which apply to the well by depressurization. Joint elements were used for the interface between different material, casing-cement-soil. And stress changing have been evaluated during methane hydrate production by calculating stresses of soil and cement along the water depth.

2. CIRCUMFERENCE ENVIRONMENT OF THE WELL

2.1. Geological property of MH reservoir

Methane hydrate reservoir which is targeted in Japan's first offshore production test is the sediment called turbidite. It has changed from sand to mud gradually in 50cm and hundreds of layer have overlapped with it. Methane hydrate bearing in this sand layer. These methane hydrate reservoir exist under hundreds meter overburden. In this research, the seabed ground is targeted where hydrate reservoir has the mud layer for the cap lock.

2.2. Composition of MH Production well

The production well will be constructed into the shallow sediments in methane hydrate exploitation besides the oil engineering. However, the production well must have bearing capacity for heavy production equipment and itself. In drilling process, firstly, the strata are drilled with muddy water. Secondary, casing pipe is putted into borehole. Then, muddy water between strata and casing pipe replace with cement slurry from bottom of the casing pipe to the top of the well. Finally, bearing capacity of this production well increase with cement hardening.

3. SIMULATION METHOD

Basic Features of Multiphase coupled analysis is as follows.

- Analysis of complex processes on multi-phase (Solids, liquid and gases).
- Disregard the flow of solid phases (soil, hydrate and ice).
- Treatment of ice solidification/melting.
- Treatment of MH dissociation/re-formation.
- Consider about mass change of each phase due to methane hydrate dissociation and re-formation.

- Consider the influence of phase changing and energy flow rule target on solid, liquid and gas phase.
- The temperature of soil particle, pore water, methane gas, methane hydrate and ice is same in local area. It is assumed that heat conduction is performed promptly.
- Disregard the deformation of solid phase in equation of continuity for hydrate and law of the conservation of energy.

4. SIMULATION MODELS

4.1. Geological Model and Boundary Conditions

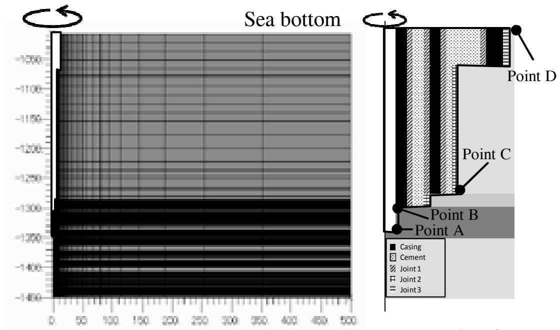
A simulation was performed assuming MH production using the depressurization method employed in the eastern Nankai Trough region in Japan. The analysis was performed assuming an elasto-plastic axi-symmetry problem. Finite element mesh for model of seabed is shown on Figure 1 (a). The model, consists of 18054 elements and 18512 nodes, has an area of 450m depth × 1000m diameter, and is located at 1000 m water depth. It is assumed that the layer 290m~340m from the ground surface as the MH-bearing layer with a MH saturation level which were investigated at the time of test boring in Nankai Trough. The conditions for each boundary are follows. (1) Top of the model are permeable for pore water and gas, and temperature fixed. (2) Periphery (Right side) of the model is permeable for water and gas, and temperature fixed. (3) Bottom of the model is permeable for water and gas, and temperature fixed. (4) Borehole (left side) is impermeable for water and gas exclude the depressurization area, and zero heat flux. The production well has three parts which are casing made with steel, cement and soil. Then, it has three set of interfaces that is shown in figure 3 (b). First interface (joint 1) is between casing and cement. Interface between cement and soil is second (joint 2). Third interface (joint 3) is between casing and soil. These interface are modeled by using joint element which proposed by Desai (1984). Methane hydrate reservoir was depressurized over 24 hours from depressurization area where the pore pressure decreases from hydrostatic pressure to 3 MPa at bottom of the borehole. This area was made to open hole. Methane gas is produced by maintaining the pressure at the area of depressurization for the next 60 days.

4.2. Material Parameter

Simulation was performed having assumed seabed ground to be liner elastic and perfect plastic material. The material parameters were shown in Table 1 & Table 2. Parameters which have no core were determined from the research in the past.

5. SIMULATION RESULTS

Figure 3(a) shows the effect of production on the distribution of water pressure. The figure expands and shows the nearby area from depressurization source. It is seen that the reduction in the pressure is centered at the area of depressurization. Depressurization area was extended rapidly in first 10 days, and the tip of depressurized area attained 20m from production well. The depressurized area expand in horizontally more next 10 days. The strata about 50m in radius was depressurized from the production well after 60 day. The layer for which depressurization was conspicuous is observed under methane hydrate reservoir. This layer has high permeability for horizontally, because the hydrate saturation compared low with upper reservoir. The hundreds of sand and mud layer have overlapped in hydrate reservoir which has various permeability,



(a) Geological modeling (b)Modeling for production well

Figure 1. Finite element analytical model (18054 elements, 18512 nodes)

Table 1. Material parameters.

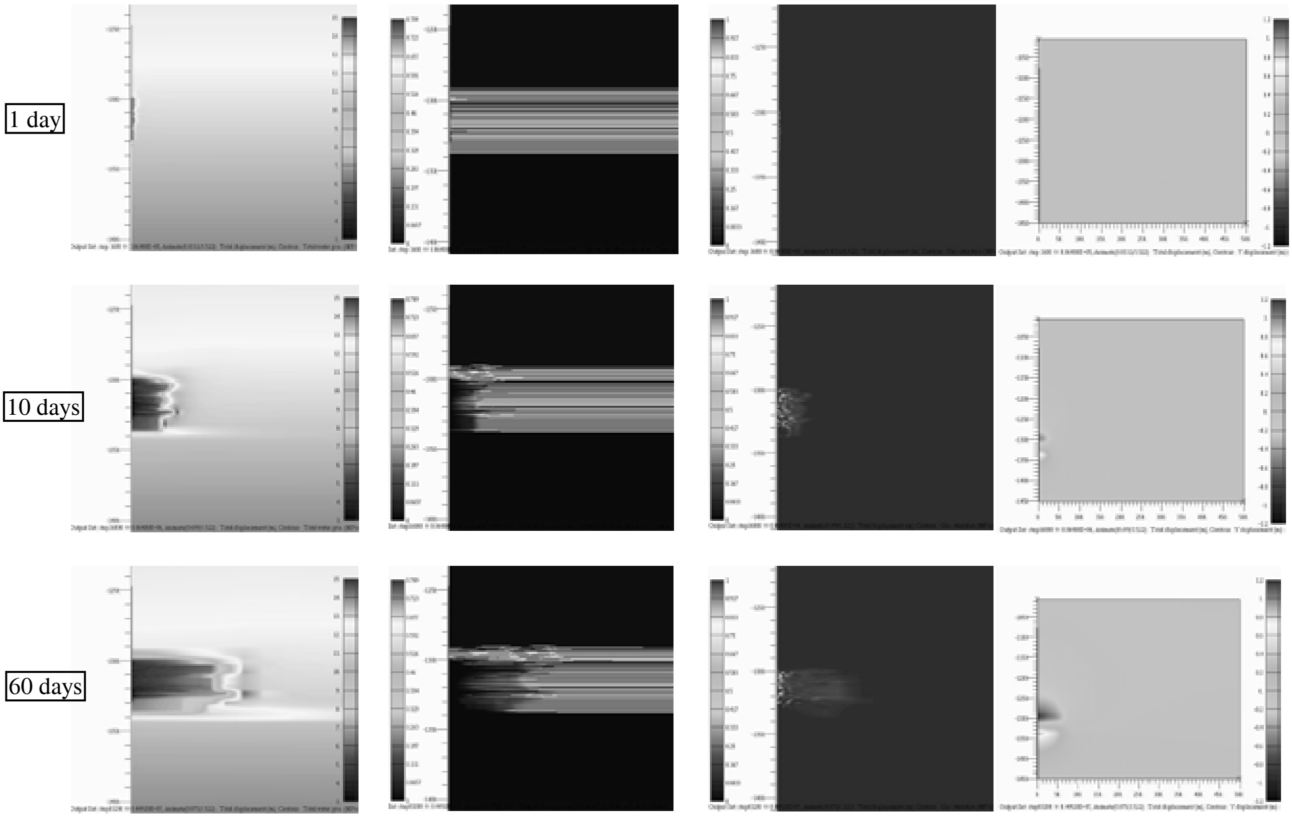
Index		unit	MH-bearing layer	Mud layer
Elastic modulus		MPa	E=700・S_h+100	80
Poisson's ratio		-	0.4	0.4
Permiability		mD	Measured value of core	
Porosity		-	Measured value of core	
MH saturation S_h		-	Measured value of core	
Temperature		K	Measured value of core	
α (Van Genuchten)		-	5.8×10^{-4}	5.8×10^{-4}
n (Van Genuchten)		-	5.3	5.3
Immovement water saturation		-	0.1	0.1
Residual gas content		-	0.1	0.1
Density	soil	kg/m^3	2650	
	water	kg/m^3	1000	
	gas	kg/m^3	0	
	MH	kg/m^3	913	
Soil specific heat	soil	J/(kg・K)	1050	
	water	J/(kg・K)	4190	
	gas	J/(kg・K)	2100	
	MH	J/(kg・K)	2010	
Thermal conductivity	soil	J/(m・s・K)	1.7	2.915
	water	J/(m・s・K)	0.586	
	gas	J/(m・s・K)	0.03	
	MH	J/(m・s・K)	0.45	

Table 2. Interface strength

Index	Unit	Joint 1	Joint 2	Joint 3
Friction angle	°	45	20	20
Cohesion	MPa	2	0	0
Shear modulus	MPa	28	28	28
Elastic modulus	MPa	80	80	80

however, it turns out that it depressurize in general uniformly. The results are because of high pressure difference about 10 MPa. Figure 3(b) shows the distribution of MH saturation ratios with the decomposition of MH. The region spreads by about 20m wide from the production well at 10 day past. The area of methane hydrate dissociated was spread gradually followed by depressurization which was shown in Figure 3(a). It is observed that the area spread horizontally 30m in 20 days, and 50m in 60 days. Dissociation of methane hydrate has not stopped yet after the 60 days in depressurized area. In addition, methane hydrate which exists 20m in radius from production well has not product completely, because it has self-preservation effect.

Figure 3(c) shows the distribution of methane gas content. Signs that methane is generated could be confirmed as methane hydrate dissociate. The elements with a high gas content being restricted to the range of 10m from the production well, though the gas generated area was still spreading. Generated gases moved at high speed with water which generated by dissociation of methane hydrate too. It seems that the high gas content elements generated because the gases from the surroundings gathers for near production well. Figure 3(d) shows the distribution of vertical displacement. It was



(a) Water pressure (b) Hydrate saturation (c) Gas saturation (d) Vertical displacement

Figure 3. Distribution of each value around production area.

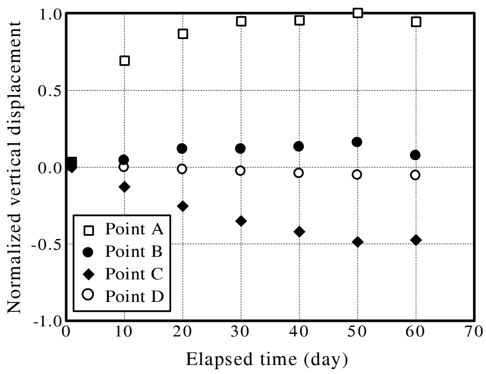


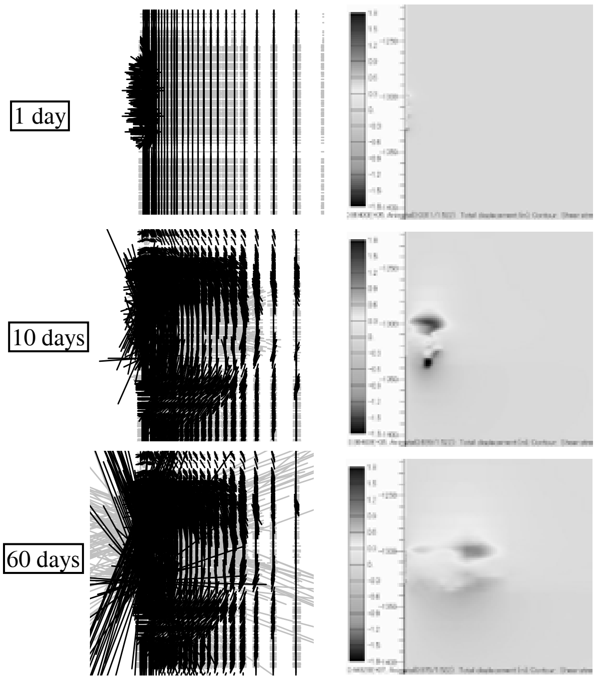
Figure 4. Normalized vertical displacement of each point.

observed that there is a neutral section from depressurization source horizontally which has not deformed vertically from the figure. A lower part of reservoir heaved vertically by effect of consolidation centered on depressurization source with 10 MPa pressure difference. On the other hand, a upper part of reservoir has deformed downward into the perpendicular. The deformation near production well appeared greatly rather than settlement of sea bottom in the result of 60 days. The area of deformation is almost same as the area of a depressurization. And furthermore, it is clear that there is a few influence of the motion on the whole stratum in case of short production.

Relationship between vertical displacement of each point of strata and elapsed time is shown in figure 4. Each point A to D were shown in Figure 1 (b), and these points are located near production well. Here, the figure shows normalized results by maximum displacement for understanding qualitatively. Point A shows maximum displacement where located at borehole bottom. This point has heaved upward into the perpendicular because the consolidations of methane hydrate reservoir and lower layer. Point B has also shown some heaving, while Point C has subsided. Therefore, it is expected that the neutral point exists between Point B and C. And Point A which is sea bottom hardly deformed. Any deformation is heading for convergence in about 50 days. However, it is necessary to examine long term analysis for understanding whole movement of seabed ground during methane hydrate production.

Maximum and minimum principal stress vector of each element were shown in figure 5(a). Maximum principal stress illustrated in blue vector and minimum principal stress illustrated in red vector in this figure. High horizontal stress appeared in neighborhood of depressurization source in first day. High stress generated by effective stress increase with reducing pore water pressure, and the stratum was horizontally compressed to the production well. Then, the vector diagram changes gradually. High horizontal stress still appeared in neighborhood of depressurization source in the result of after 10 days. However, High vertical stress has appeared on the ground about 10m away for depressurization source. And the maximum principal stress vectors are distributed like arch structure over the upper and lower sides. Moreover it have supported upper layer. Therefore, settlement of sea bottom hardly appears in case of short production. It become clear that arching effect prevent settlement of upper layer and sea bottom by a depressurized area spreads almost circularly.

Figure 5(b) shows the shear strain distribution at the seabed. Note that shear strains occur at the boundary of MH-bearing layer and the upper/lower layer like a wedge as a result of differential settlement. Shear stress which caused by differential settlement becomes maximum in 10 days past from depressurization start, and it reached about 2MPa shear stress and 3% of shear strain in this analysis.



(a) Principal stress of each element near depressurization area

(Maximum stress, Black; Minimum stress, Gray)

(b) Shear stress

Figure 5. Stress vector and shear strain by depressurization.

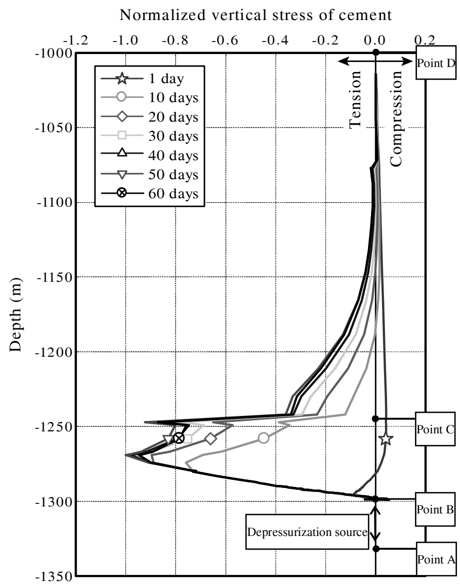


Figure 6. Normalized vertical stress σ_y of cement

Figure 6 shows the relationship between water depth and vertical stress of cement during methane hydrate production. The results were plotted for each different elapsed time, and compression is positive in the figure. In addition, it was normalized by maximum stress to make qualitative understanding easily. Firstly, compressive stress appeared from seabed to -1280m and tensile stress appeared below on the first day. The initial stress by self-weight is distributed linearly. However, tensile stress has occurred because production well was jerked by the settlement of depressurized area. Ten days after, tensile stress was applied dramatically on where -1100m to -1300m. It is considered that the high tensile stress acted on cement through the interfaces of cement and strata because the upper layer deform downward by methane hydrate reservoir had consolidated. The stresses decline 50 days after in this simulation.

It is confirmed that high tensile stress appear on cement about 50m range above the depressurization area, and compression stress appear on open hole which is depressurization area. Moreover, it became clear that near Point B where is a junction of a casing and open hole part becomes neutral point.

6. CONCLUSIONS

A multi phase coupled simulator using finite element method named "COTHMA" had used for predicting stresses and deformation of methane hydrate vicinity production well and the deep seabed ground which simulating NANKAI trough where is planned as Japan's first offshore production test area.

According to analytical results, depressurization area was extended rapidly in first 10 days, and the tip of depressurized area attained 20m from production well. the elements near production well are compressed by increased effective stress due to depressurization. Then, a lower part of reservoir heaved vertically by effect of consolidation centered on depressurization source with 10 MPa pressure difference. On the other hand, a upper part of reservoir has deformed downward into the perpendicular. And there is a neutral section from depressurization source horizontally which has not deformed vertically.

The maximum principal stress vectors are distributed like arch structure over the upper and lower layer. Moreover it have supported upper layer. Therefore, deformation of seabed ground near production well is greater than bottom of sea's. However, high tensile stress appear on cement about 50m range above the depressurization area, and compression stress appear on open hole which is depressurization area. It was found that the settlement of the seabed cause negative friction along production well.

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