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The Effects of Gas Hydrate Dissociation on the Stability of Pipeline in Seabed

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ABSTRACT

Based on an assumed vertical pipeline in seabed, which contains sand and gas hydrate sediment, the deformation and stress of pipeline and sediment are numerically simulated with the different area of gas hydrate dissociation by using the business software ABAQUS. The effects of gas hydrate dissociation area and the thickness of overlaying sand sediment on the stability of pipeline are estimated. It is shown that gas hydrate dissociation obviously affects the deformation of pipeline and sediment. With the expansion of dissociation area, the deformation of pipeline and sediment increase obviously, the shear stress and the stress yielding area in sediment increase too. The pipeline is elastic and stable first, and then becomes to bend and finally be whole instability. When the thickness of overlaying sand sediment increases, the deformation of pipeline and surrounding sediment also increase because of the gravity and the sliding force of overlaying sand sediment.
KEY WORDS: pipeline; gas hydrate dissociation; simulation; stability.

INTRODUCTION

Gas hydrate is a new potential source of energy in the 21st century. More and more countries concentrate on surveying, studying gas hydrate now, and trying to produce methane gas from methane gas hydrate sediment in the future. But most of the previous researches pay much more attention to the exploitation of gas hydrate and concern about the in-situ investigation of natural gas hydrate and some laboratory simulation tests on synthesized samples containing methane gas hydrate.

Previous studies have been concluded that gas hydrate dissociation can lower the effective stress in gas hydrate sediment and induce slope failures. The second Storegga slide in Norway (Locat J, Lee HJ, 2002; Hovland, M, Orange, D et al, 2001), Cape Fear slide in east coast of America and the landslide in continental shelf of west Africa (Kayer RE, Lee HJ, 1991; Sultan N, Cochonat P, Foucher J, 2004) and some other slides (Gilles, G, David, G, and Aaleksandr M, 1999) in ocean are all resulted by gas hydrate dissociation. So it is very important to know if the offshore structures in gas hydrate sediment are stable when gas hydrate dissociates.

Till now, there are not any analyses and simulating calculations of effects on the stability of offshore structure resulted by gas hydrate dissociation. But the effects of gas hydrate dissociation on the stability of pipeline must be considered. The following explanations give how and why gas hydrate dissociation affects the stability of pipeline inserted in gas hydrate sediment:

1) Firstly, when depressurizing, thermal heating and other production techniques are used in exploitation of gas hydrate, gas hydrate begins to be melted and release gas, the contacts among soil particles become weaker and weaker, and the fabric structure of soil will be gradually disturbed. When more and more gas changes from solid state to gas plus water state, the soil will contain relatively large amount of gas dissolved in the pore fluid and the pore pressure will increase and reach the gas saturation pressure in undrained condition, so the effective stress of gas hydrate sediment decreases.

2) Secondly, the presence of gas hydrate may prevent the normal sediment compaction processes and gas hydrate dissociation may generate an underconsolidated soil with a significant weakening of soil resistance.

3) Finally, with the increase of gas hydrate dissociation area, the degradation of shear strength of gas hydrate sediment increases and the sediment failure in the end. When the surrounding sediment starts to slide and collapse, the pipeline inserted in gas hydrate sediment starts to lose its stability or even be destroyed.

By use of the business software ABAQUS, and based on the physical and strength parameters of sand sediment and methane gas hydrate sediment, we assume a typical site which have a layer of gas hydrate sediment beneath sand sediment, and calculate the deformations and the stresses of pipeline and sediment with different gas hydrate dissociation areas. The effects of gas hydrate dissociation area and the thickness of overlaying sand sediment on the stability of pipeline are analyzed.

ASSUMPTIONS

The sketch of sediment profile and pipeline we assumed is shown in Fig.1. The pipeline for transporting gas is vertically inserted in sediment containing gas hydrate. The thickness of overlaying sand sediment and gas hydrate sediment is separately indicated by h_1 and h_2, the length of the steel pipeline inserted in sediment is 100m, its inner diameter is 40m and wall thickness is 0.02m. The symbol β stands for the slope angle of the seabed and here is thought as 3^0.

In order to simulate the variety of layered sediment, three different sediment profiles are supposed.

1) h_1 is 0m while h_2 is 100m.
2) h_1 is 25m while h_2 is 75m.
3) h_1 is 50m while h_2 is 50m.

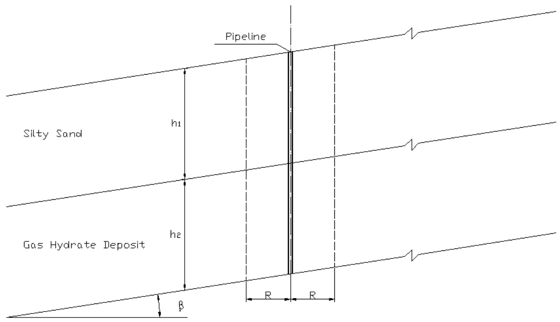


Fig.1 The sketch of pipeline and sediment profile

The diameter of gas hydrate dissociation R is defined as the horizontal distance from the symmetry axis of pipeline to the surrounding sediment and indicates the area of gas hydrate dissociation. Here, R is separately considered as five situations of 5m, 20m, 40m, 80m and infinite.

ABAQUS Version 6.7 is used here to model the interaction between a buried pipeline and the surrounding soil in two-dimensional pipe-soil interaction elements. The contacting surface between pipeline and the surrounding soil is defined as contact pair and then the “master” and “slave” surface method is adopt. In Abaqus/Standard element library, the pipeline is modeled with the beam element while a contact is set up between the pipeline and the surrounding sediment. Hard contact in normal direction and non-friction contact in tangent direction are also adopted.

When considering the contact surface of pipe-soil, a first-order element, which will form the slave surface, is applied to the soil model. In numerical simulation, the computational area is considered as 200m horizontal length by 100m vertical depth. The satisfied finite element mesh is obtained by computation and comparison. The element mesh is finally determined as 1m*1m within 100m long of sediment and 2m×4m outside 100m long of sediment.

The sediment is considered as a body of infinite half-space and the detailed boundary conditions are defined as the follows:

1) The deformations in three directions are all restricted at the bottom of gas hydrate sediment, $U_1=U_2=U_3=0$.
2) The side surfaces of the sediment are restricted and the vertical deformation is permitted, $U_1=U_3=0$.
3) The symmetry surface of the sediment is constrained in normal direction, $U_1=0$.
4) The confined condition of the symmetry rotation axis of the pipeline is the same as that of the soil, $U_1=0$.

MODEL AND PARAMETERS

The initial earth stress field, also called initial gravity field, exists in the sediment before the pipeline is settled in seabed. So we put the gravity of sediment on the foundation, and then use the self-balance power of the initial stress field in the program to form the initial gravity stress field and think it as the initial stress field. The field variables can be applied to deal with the material parameters which change with the different areas of gas hydrate dissociation.

It should be noted that some assumptions in the simplified model are limited in the numerical simulation and the explanation are given in the following items:

1) Gas hydrate sediment is assumed on the hard sediment and the friction between gas hydrate sediment and sand sediment is very big. The pipeline is also inserted down to harder soil sediment. So the bottoms of gas hydrate sediment and pipeline are all considered as fixed ends.

2) The deformation of contact elements among gas hydrate sediment itself are thought to be continuous before and after gas hydrate dissociation, and the overlaying sand sediment doesn’t slide along the beneath gas hydrate sediment.

3) Although the process of strength decrease of sediment caused by gas hydrate dissociation is dynamic, gas hydrate dissociation can be simply thought to happen in a short time. So the dynamic process of gas hydrate dissociation isn’t taken for in the computation.

The elastic model is adopted for the steel pipeline and the Mohr-Columb constitutive model for sand or gas hydrate sediment. The parameters for pipeline are as follows: the density ρ=7800kg/m^3, the elastic modulus E=2.09*10^{5}MPa and the Poisson’s ratio ν=0.3. For sand sediment without gas hydrate, ρ=1980kg/m^3, E=18.9MPa, ν=0.2, the cohesion C=0 and the inner friction angle ϕ=38^0.

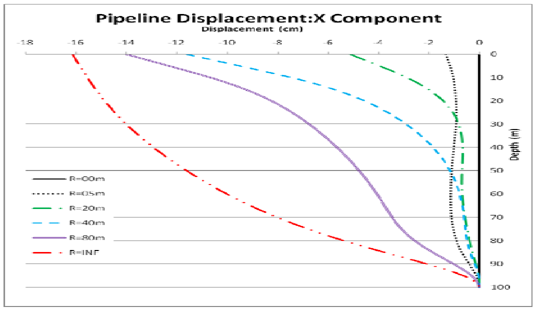
The parameters of gas hydrate sediment before and after gas hydrate dissociation are all based on the test results of sediment containing natural gas hydrate obtained by Winters (Winters WJ, Pecher IA et al, 2004; Winters WJ, Waite WF et al, 2007) and take a consideration of William’s study(William, JW, Ingo, AP, William, FW et al, 2004). They are as follows: ρ=1980/1920kg/m^3 (before/after), E=186/26.8MPa, ν=0.2/0.2, and ϕ=39.4^0/34^0.

RESULTS AND DISCUSSION

The Displacement of Pipeline

The horizontal displacement of pipeline before and after gas hydrate dissociation under three different conditions of sediment profile is shown in Fig.2a-2c. Fig.2a shows that the displacement of pipeline increases with the development of gas hydrate dissociation area when pipeline in non-overlaying sand sediment. The pipeline first behaves elastically, and then gradually becomes to bend seriously, finally falls down straight when the dissociation diameter is bigger than 80m. The maximum displacements under different dissociation areas all occur at the top of pipeline. The most dangerous situation is when gas hydrate fully dissociates and the maximum displacement is about 0.16m.

Fig.2b-2c show the displacement of pipeline with the diameter of gas hydrates dissociation when pipeline in different thickness combinations of overlaying sand sediment and gas hydrate sediment. Comparing Fig.2a with Fig.2b-2c, it is found that the displacement of pipeline becomes a little smaller and smaller when the thickness of overlaying sand sediment is from 0 to 20m and 50m. Moreover, the deformation of pipeline in overlaying sand sediment is held back because the strength parameters of the sand sediment are constant. At the boundary of these two sediments, as is clearly shown in Fig.2c, the deformation trend of pipeline obviously changes and the pipeline has a bigger and bigger bending. So in one aspect, the overlaying sediment is helpful to reduce the displacement of pipeline especially at the top of pipeline. But in the other aspect, the existence of boundary between the two sediments makes the pipeline have a serious bend and may be broken down at this bending point.



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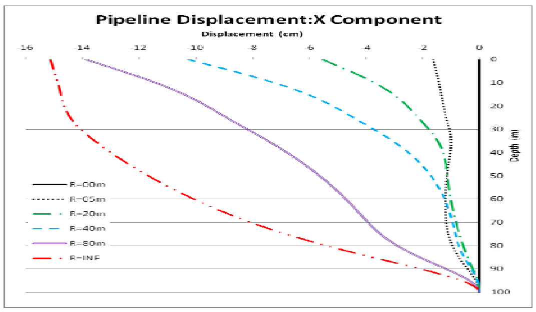

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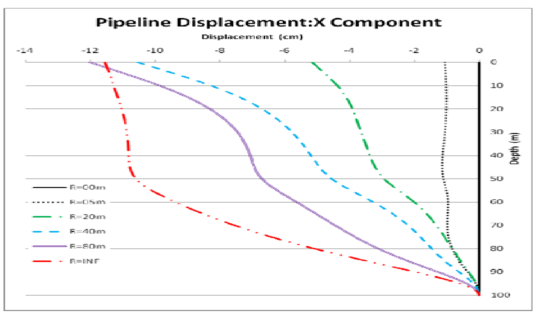
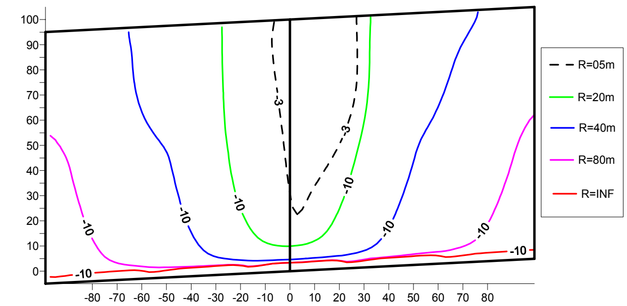


(c)

Fig.2 The displacement of pipeline versus the diameter of gas hydrate dissociation: a) under the condition of h_1=0m, h_2=100m, b) under the condition of h_1=25m, h_2=75m, c) under the condition of h_1=50m, h_2=50m.

The Settlement of Sediment

Fig.3a-c shows the settlement of sediment versus the diameter of gas hydrate dissociation under three different conditions of sediment profile. Here we only present the contours for a certain deformation value in centimeter under each gas hydrate dissociation diameter. It's noted that the settlement of sediment inside of contour is bigger than the settlement on the contour. It is shown that the settlement of sediment increases with the diameter of gas hydrate dissociation and the effect areas of settlement are different when the thickness of gas hydrate sediment is obvious different. The more the gas hydrate sediment is, the larger the settlement of sediment becomes. And also, the more close to pipeline the surrounding sediment is, the bigger the settlement of sediment get. When the dissociation diameter is bigger than 80m, almost all elements of the sediment, which in 100m depth by 200m length, settle down than 0.10m and the landslide may happen.



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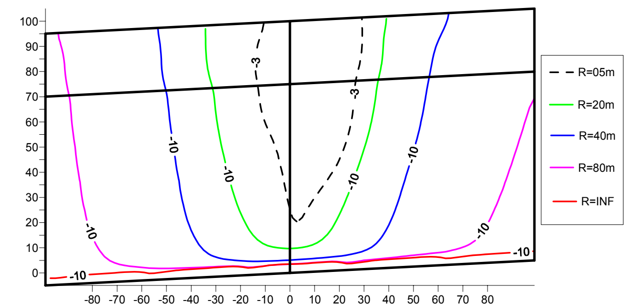

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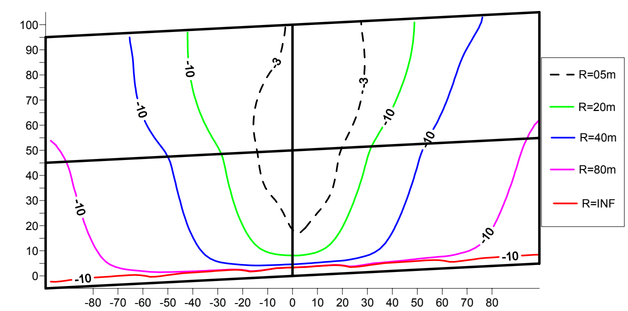


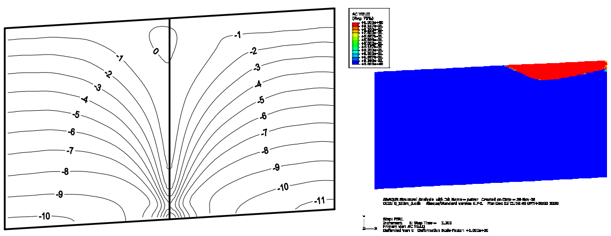
(c)

Fig.3 The settlement (cm) of sediment versus the diameter of gas hydrate dissociation: a) under the condition of h_1=0m, h_2=100m, b) under the condition of h_1=25m, h_2=75m, c) under the condition of h_1=50m, h_2=50m.

The Shear Stress and Yield of Sediment

Fig.4a-e show the shear stress and yield contour of sediment with the diameter of gas hydrate dissociation when the whole 100m depth seabed is only full with gas hydrate sediment. The red zone in each right figure indicates that the shear stress induced by sediment gravity is bigger than the shear strength of sediment itself and the sediment is in yield or failure state. It is shown that the shear stress and the area of yield surface of surrounding sediment increase and the maximum shear stress also strongly relates to the dissociation area with the development of gas hydrate dissociation area,

Before gas hydrate dissociation, the shear stress of sediment distributes symmetrically to the vertical axis of pipeline and there is a little area close to the right top of sediment surface in failure state. But after gas hydrate dissociation, the yield area gradually expands with the area of gas dissociation. Firstly, the upper surface and the middle bottom and the surrounding boundary of gas hydrate dissociation develop stress yield and the area of upper surface is bigger. Then, the area of stress yield of sediment becomes bigger and bigger, the area of stress yield at the bottom of sediment increases rapidly, and in the same time, that in the upper surface of sediment decrease obviously. Finally, when gas hydrate dissociates wholly, almost the stress of whole sediment reaches yielding and the sediment begin to failure. So, with the increase of area of gas hydrate dissociation, the pipeline inserted in gas hydrate sediment will gradually lose its stability because of the sediment yields or failures.



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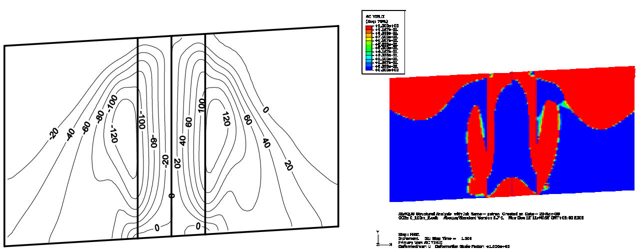

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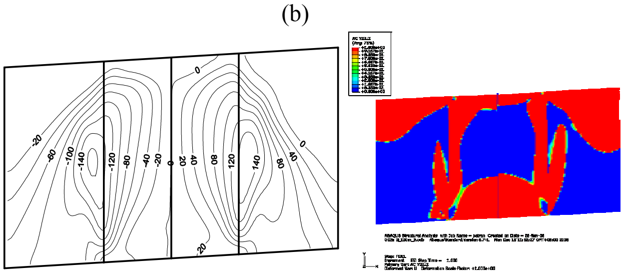

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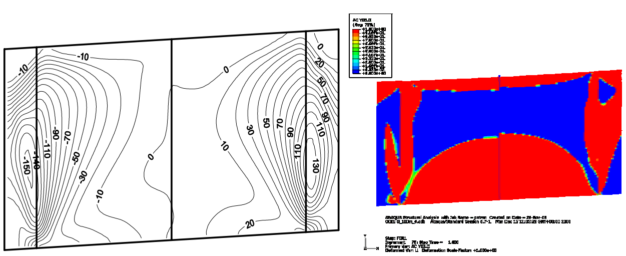

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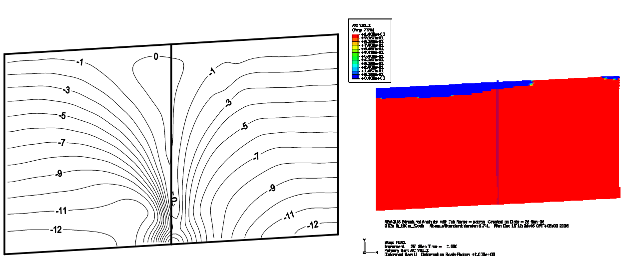

(e)

Fig.4 The shear stress (kPa) and stress yielding zone in sediment versus the diameter of gas hydrate dissociation under the condition of h_1=0m, h_2=100m: a) R=0m, b) R=20m, c) R=40m, d) R=80m, e) R=infinite.

CONCLUSIONS

In this paper, we assume a deep-sea sediment containing gas hydrate and a pipeline inserted in it, simulate a two-dimensional pipe-soil interaction by ABAQUS software and obtain the deformation of the pipeline and the settlement and shear stress of the surrounding soil. The numerical simulation is completed under the conditions of different gas hydrate dissociation area and different thickness of overlaying sand sediment. The stability of pipeline and sediment with gas hydrate dissociation is evaluated and the following conclusions are obtained:

1) With the development of gas hydrate dissociation area, the displacement of pipeline increases in every sediment layer. The maximum displacement is about 0.16m when gas hydrate fully dissociates. The deformation process of pipeline behaves from elastics, bending, to fall down straight. The overlaying sediment is helpful to reduce the displacement of pipeline especially at the top of pipeline in one aspect. But in the other aspect, it makes the pipeline bend seriously and may be broken down at the boundary of two sediments.

2) With the development of gas hydrate dissociation area, the settlement of sediment also increases. The affected settlement areas are different with the different thickness of gas hydrate sediment. When gas hydrate sediment is more and closer to pipeline, the settlement of sediment is bigger. Even more, when the dissociation diameter is bigger than 80m, almost all sediments settle down than 0.10m and begin to be landslide.

3) With the development of gas hydrate dissociation area, the shear stress and the area of yielding surface in sediment increase too. The pipeline inserted in gas hydrate sediment will gradually lose its stability when the sediment develop a bigger and bigger space of stress yielding due to the increase of area of gas hydrate dissociation.

Based on the above numerical simulation and analyses, it is suggested that the area of gas hydrate dissociation in gas hydrate sediment surrounding pipeline should be controlled strictly during gas production in order to ensure the safety and stability of pipeline .

ACKNOWLEDGEMENTS

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