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Mechanism of soil stratum instability induced by hydrate dissociation

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ABSTRACT

Gas hydrate dissociation may lead to soil stratum instability such as marine landslides in hydrate-bearing sediments. In this paper, centrifugal tests were conducted to investigate the soil responses and stratum instability of a 14° slope during hydrate dissociation under centrifugal accelerations of 50*g* and 100*g*, different boundary conditions and heating modes. New phenomena such as sliding of the over layer, layered fractures between the hydrate layer and the over layer, and fractures in the over layer were observed. The fluid pressures, horizontal displacements and vertical displacements of the soils were measured and compared under different conditions. The observed mechanisms and decoupled formulations considering heat transfer, fluid seepage, soil deformation and critical soil failure were presented and discussed. The formation of layered fractures during hydrate dissociation is regarded as an important factor leading to the instability of the slope.

1. Introduction

Thermal disturbances to a hydrate stratum during hydrate exploitation or natural environmental changes may cause the dissociation of hydrate, releasing 164 times of gas in volume and 0.8 times of water into the pore space (Xu and Germanovich, 2006). The expansion of the hydrate dissociation zone will greatly reduce the stiffness and strength of the hydrate-bearing sediment (HBS) (Lu et al., 2008a, 2008b; Song et al., 2014; Jiang et al., 2014; Hyodo et al., 2014; Zhang et al., 2015a). Excess pore fluid pressure develops in a low permeability hydrate stratum. The soil responses during hydrate dissociation may lead to geological and engineering hazards such as marine landslides, seabed subsidence, destruction of oil pipes and gas blowouts (Sultan et al., 2004; Xu and Germanovich, 2006; Kwon et al., 2008; Kwon and Cho, 2012; Lu et al., 2013; Zhang et al., 2014).

The marine landslides caused by hydrate dissociation are associated with small slope gradients. The complex processes such as coupled physical and chemical interactions, phase transformation, soil softening and high excess pore pressures involved in the marine slides make such slides much different from conventional landslides (Kimoto et al., 2010; Klar et al., 2010; Kwon and Cho, 2012). The mechanisms of hydrate dissociation-induced marine landslides have not been fully understood.

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Limit equilibrium methods considering excess pore fluid pressure were presented to investigate the instability of marine slopes (Kayen and Lee, 1991; Borja et al., 2012), but the evolution of the soil failure mechanisms were not considered. Briaud and Chaouch (1997) presented possible tensile failure mechanisms such as hydraulic fracturing and cavity expansion during hydrate dissociation. Zhang et al. (2011) observed layered fractures and gas outburst in the experimental simulation of thermal-induced hydrate dissociation in a Perspex glass cylinder. Layered fractures also occurred during hydrate dissociation in a one dimensional geotechnical centrifugal test, and changes in temperature, pressure and deformation in HBS were obtained (Kwon et al., 2013).

The physical mechanisms of soil stratum instability induced by hydrate dissociation are still not well understood. The time and space relationships between small and large scale soil failures and the damage degree should be made clearer for the evaluation of engineering system safety. Especially, it is necessary to validate the gravitational effects and the mechanism of stratum instabilities at engineering scales. Hence, large scale physical modeling is required to obtain insight into the failure evolution and physical mechanisms during and after hydrate dissociation.

In geotechnical engineering, centrifugal testing is an effective tool to reproduce the gravitational effect and obtain the failure behavior of a large scale soil slope. Based on scaling laws, the modeling concerns with replicating an event comparable to what might exist in the prototype and the results can be extrapolated to a prototype situation (Taylor, 1995). Hence, centrifugal testing is a good choice for simulating the evolution of stratum instabilities such as large scale slides during thermal induced hydrate dissociation.

Zhang et al. (2015b) conducted a centrifuge experiment considering the evolution of the hydrate dissociation scales around a heating rod and the effect on the stratum instability. The results showed that large pore pressures and large displacements developed and layered fractures occurred during hydrate dissociation. These phenomena trigger new concerns on what will happen at different hydrate dissociation rates and different boundary constraints to the soil layers, considering the practical environmental conditions. Further centrifuge tests are needed to understand the physical mechanisms of soil instabilities during dissociation.

According to geological surveys and drilling in South China Sea, typical hydrate strata are located from 10 m to 300 m below the seabed at a water depth of about 1000 m; the slopes of the soil layers are in the range of 3–15°. This paper aims at investigating the physical mechanisms of soil stratum instabilities during thermal induced hydrate dissociation by geotechnical centrifugal tests, referring the geological and geotechnical conditions in the hydrate zone in South China Sea. In Section 2, details of the geotechnical centrifugal tests are presented, such as the preparation of soil layers, heating modes and boundary constraints. In Section 3, the test results and observations on physical mechanisms are reported, such as pore fluid pressures and vertical and horizontal displacements. In Section 4, the decoupled mathematical formations for heat transfer, seepage and consolidation, and critical condition of soil failures during hydrate dissociation are presented and discussed.

2. Description of the geotechnical centrifugal tests

2.1. Scaling laws

The basic principle of centrifuge modeling is as follows: if an acceleration of N times gravity g is applied to a material with density ρ, then the vertical stress at depth l_m in the model (indicated by subscript m) is given by $\sigma_m = \rho N g l_m$, and the prototype (indicated by subscript p) stress is $\sigma_p = \rho g l_p$. Thus to produce identical stress conditions in the model, i.e., $\rho N g l_m = \rho g l_p$, the model dimensions must be scaled at $l_p = N l_m$.

Zhang et al. (2015b) presented the scaling laws for centrifugal testing of stratum failures induced by hydrate dissociation. The characteristic times for four physical processes during hydrate dissociation, which are heat transfer, phase transformation, fluid seepage, and soil deformation, differ by two orders of magnitude. Hence the four processes can be decoupled (Tan, 2011). Accordingly, the soil behavior and failure during hydrate dissociation can be analyzed as follows. First, the heat induced temperature difference $T_H - T_0$ leads to the hydrate dissociation and expansion in HBS with a hydrate saturation of S_h. The heating modes determine the length l and fluid pressure p in the dissociation zone based on the heat transfer involving phase transformations. Second, the seepage and consolidation of HBS occur under the effects of self-weight. Finally, the soil layer fails once the critical condition of instability is satisfied. The heating modes affect the expanding speed and length of hydrate dissociation, and the boundary constraints affect the deforming speed and failure degree of the soil layers. Here, the heating modes and boundary constraints are considered to be two controlling factors.

2.2. The centrifuge and model specimen preparation

The geotechnical centrifuge at Tsinghua University was used in the tests. The rotational radius of the centrifuge was 2.0 m, and the maximum centrifugal acceleration was 250*g* (Zhang et al., 2015b).

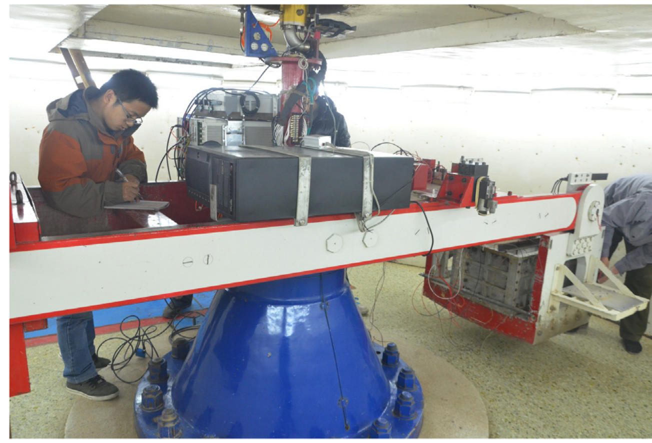

Fig. 1. The centrifuge and the model box.

The dimensions of the model box for the centrifugal tests were 0.6 m in length, 0.35 m in width, and 0.4 m in height (i.e., 60 m in length, 35 m in width, and 40 m in height in prototype scale at an acceleration of 100*g*). The total weight of the model was about 120 kg in each test. Fig. 1 shows a photo of the centrifuge and the model box.

The clay in the tests was obtained by drilling in the China Dongsha hydrate area in South China Sea, and the soil layers were prepared according to the in-situ conditions. The slope of the hydrate stratum in South China Sea is about 3–15°, with the typical slope being 14° based on results of drilling and testing with a gas hydrate-related bottom simulating reflector in 2013 (Sha et al., 2015a, 2015b).

Two layers, the hydrate layer and the over layer were set in the model at a slope of 14°. The dry density of the hydrate layer before hydrate formation was 1.1 g/cm^3 and the porosity was 60%. Tetrahydro-furan (THF) hydrate sediment was synthesized because it is similar to HBS in mechanical and thermal properties and can be prepared uniformly (Yun et al., 2007). The preparation of the hydrate layer was as follows. Firstly, the clay was mixed with the THF solution. In the solution, the water volumetric fraction was 92% to keep the THF hydrate saturation at 40% after formation. Secondly, the model box was placed at a slope of 14°, and filled with the test clay, keeping the dry density at 1.1 g/cm^3. Finally, the model box was placed in the refrigerator for about two days with its temperature set at 2 °C until the THF hydrate formed.

The over layer was prepared after the formation of the hydrate layer, and the density of the layer was set at 1.3 g/cm^3, and the porosity was 52%. The clay was drilled and sampled from the seabed over the hydrate layer. The cohesions of the over layer and the hydrate dissociation layer were 35 kPa and 7 kPa, respectively, and the stress path can be referred to Zhang et al. (2015b).

2.3. Test setups

The geotechnical response of the soil layers and the mechanism of soil stratum instabilities are concerned during thermal injection exploitation of hydrate in the hydrate layer or exploitation of hot gas underlying the hydrate layer in South China Sea. Table 1 shows the details of six centrifugal tests. Different centrifugal accelerations (50*g* and 100*g*) were adopted to simulate the effect of the absolute thicknesses of soil layers, and the geometrical scale effect was concerned. Heating mode HM1 was adopted to simulate the natural heating of the over layer above the hydrate layer owing to the rising temperature of the seawater. Heating modes HM1, HM2, HM3 and HM4 were used to investigate the effect of the hydrate exploitation modes (i.e. multi-wells, two wells and one well) and